2. System Considerations

2.1 INTRODUCTION

A nuclear air cleaning installation is one of an assemblage of interrelated and interactive parts that include a ventilation system, the contained space served by that system (i.e., glove box, hot cell, room, or building), and the processes carried out there. The design of an air cleaning installation has a direct bearing on the performance and operating costs of the ventilation system of which it is a part, and equally, the design of the ventilation system directly affects the performance and costs of the air cleaning facility. This chapter discusses, in general terms, some of the factors that must be considered when designing nuclear air cleaning facilities.

2.2 ENVIRONMENTAL CONSIDERATIONS

The complexity of the air cleaning system needed to provide satisfactory working conditions for personnel and to prevent the release of radioactive or toxic substances to the atmosphere depends on the nature of the contaminants to be removed (e.g., radioactivity, toxicity, corrosivity, particle size and size distribution, particle shape, and viscidity); on heat, moisture, and other conditions of the environment to be controlled; on the probability of an upset or accident; and on the extent of hazard in the event of such upset.

2.2.1 Zoning

Workroom ventilation rates are based primarily on cooling requirements, the potential combustion hazard, and the potential inhalation hazard of substances present in, or which could be released to, the workroom. Concentrations of radioactive gases and aerosols in the air of occupied and occasionally occupied areas should not exceed the concentration guides (CG) established for occupationally exposed persons under normal or abnormal operating conditions, and releases to the atmosphere must not exceed the permissible limits for nonoccupationally exposed persons.[1,2] Because radioactive gases and aerosols might be released accidentally in the event of an equipment failure, a spill, or system upset, the ventilation and air cleaning facilities must be designed to maintain airborne radioactive material within prescribed limits, even following the worst conceivable accident that could occur in the plant.[2] Control is made more difficult by the "as low as reasonably achievable" (ALARA) requirements which, at least for light water reactors, restrict gaseous and airborne particulate effluents to levels such that continuous exposure of persons in unrestricted spaces of the plant and its environs will not exceed the design objective annual dose limits set forth in Appendix I of 10 CFR 50.[3] These guides limit annual dose to the whole body to 5 millirems, annual dose to the skin to 15 millirems, and annual radioiodine exposure to the thyroid to 15 millirems. In addition, the calculated air doses due to gamma and beta radiation should not exceed 10 and 20 millirads respectively. These limits are design objectives and can be modified when rationalized by a cost-benefit analysis.

Radioactive materials may be grouped as shown in Tables 2.1 and 2.2 with respect to relative inhalation hazard. Quantities of radioactive materials greater than those indicated in Table 2.2 must be handled within a special containment, such as a hot cell or glove box, which often has ventilation and/or exhaust facilities independent of those serving the building space in which the special containment is located. The current CGs for radioactive substances in air are specified in 10 CFR 20.[1] A building or facility can be divided into confinement zones with respect to the hazard classes shown in Table 2.2 and based on the criteria shown in Table 2.3. The limits given in Table 2.3 are guides and should not be considered as absolute. By introducing such indexes of potential hazard and limitations on the quantities of materials that can be handled, it is possible to establish a basis for ventilation and air cleaning

Table 2.1. Hazard classification of radioisotopes

Hazard class	Hazard	CG, air (Ci/liter)	Amount of radioactive materials permitted[a] (μCi)
1	Very high	$\leq 10^{-13}$	0.1
2	High	10^{-13} to 10^{-11}	1.0
3	Moderate	10^{-11} to 10^{-9}	10.0
4	Negligible	$\leq 10^{-9}$	100.0

[a]Amount of radioactive material that can be handled without special protection for personnel.

requirements in various parts of a building or plant. Figure 2.1 illustrates a typical zoning plan for a nuclear facility showing permitted occupancies, pressure differentials between zones required for proper ventilation and contaminant control, and zone assignments. Not all of the zones listed in Table 2.3 would be required in all buildings, and an entire building could quite possibly be designated as a single zone. Zones are defined, with respect to function and permitted occupancy, as follows:

Table 2.2. Classification of isotopes according to relative radiotoxicity based on inhalation hazard[a] amounts (Ci) equivalent to 1 g of Pu-239 (HEP)[b]

Italicized isotopes are fissile and require special consideration for nuclear safety

Class 1 (Very high radiotoxicity) HEP $\leq$ 0.07	Sr-90 + Y-90, Po-210, Po-210 + Bi-210, Ra-226, Th-228, U-232, *Np-236, Pu-238, Pu-239, Pu-240, Pu-241, Am-241, Am-242^m, Cm-242, Am-243, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Bk-249, Cf-249 Cf-250, Cf-251, Cf-252*
Class 2 (High radiotoxicity) HEP = 0.86 to 17	Na-22, P-32, Ca-45, Sc-46, V-48, Fe-59, Co-58, Co-60, Ni-63, Zn-65, Rb-86, Sr-89, Y-91, Zr-95 + Nb-95, Ru-103, Ru-106 + Rh-106, Ag-105, Ag-110, Cd-109 + Ag-109, Cd-115, In-114, Sn-113, Sb-122, Sb-124, Sb-125, I-131, Cs-134, Cs-137 + Ba-137, Ba-140 + La-140, Ce-144 + Pr-144, Pm-147, Sm-151, Eu-152, Eu-154, Tm-170, Hf-181, Ta-182, Ir-192, Hg-203, Tl-204, Bi-210, At-211, *U-233*,[c] Th-234 + Pa-234, *Np-237, Pu-242*
Class 3 (Moderate radiotoxicity) HEP = 22 to 220	Be-7, Na-24, S-35, K-42, Ca-47, Sc-47, Sc-48, Mn-52, Mn-54, Fe-55, Mn-56, Cu-64, Ga-72, As-74, As-76, As-77, Se-75, Br-82, Sr-85, Y-90, Nb-95, Mo-99, Pd-103 + Rd-103, Rh-105, Pd-109, Ag-111, Cd-115, Sb-122, Te-127, Ba-131, La-140, Ce-141, Pr-142, Pr-143, Nd-147, Ho-166, Sm-153, Ho-170, Lu-177, W-181, W-185, W-187, Re-183, Re-186, Os-191, Ir-190, Ir-192, Ir-194, Pt-191, Pt-193, Au-196, Au-198, Au-199, Hg-197, Tl-200, Tl-201, Tl-202, Ac-227, *pure U-233*, U-234
Class 4 (Slight radiotoxicity) HEP > 430	H-3, C-14, F-18, Cl-36, A-37, Cr-51, Ni-59, Ge-71, Kr-85, Tc-98, Tc-99, Ru-97, Rh-103, Te-129, I-129, I-132, Xe-133, Pb-203, *U-235*, U-236, natural thorium, U-238, natural uranium

[a]These values are based on inhalation and immersion (for inert gases) hazard only. Other factors that must be considered are criticality, chemical toxicity and reactivity, and pyrophoricity.

[b]HEP = hazard equivalent plutonium.

[c]$\leq$ 500 ppm U-232.

Note:

$HEP = (2.16 \times 10^9)(CG \times A)$

where

$CG = \mu Ci/cm^3$ for 40-hr week;

$A = g/Ci$ or 0.1, whichever is greater.

Sample calculation—Determine curie HEP for Am-241.

CG 40-hr week for Am-241 = $6 \times 10^{-12}\ \mu Ci/cm^3$

Inverse specific activity (g/Ci) = 0.311

$\therefore HEP = 2.16 \times 10^9 \times 6 \times 10^{-12} \times 0.311$

$= 4.03 \times 10^{-3}$

Therefore, 4.03×10^{-3} Ci of Am-241 has the same hazard equivalent potential as 1 g of Pu-239.

Source: *Procedures and Practices for Radiation Protection, Health Physics Manual*, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Table 2.3. Zoning of facilities based on radiotoxicity of materials handled

Radiotoxicity of isotopes	Quantity of material handled vs radiotoxicity			
	Zone I	Zone II	Zone III	Zone IV
Very high[a]	>10 mCi	10 μCi–10 mCi	0.1 μCi–10 μCi	0–0.1 μCi
High	>100 mCi	100 μCi–100 mCi	1.0 μCi–100 μCi	0–1.0 μCi
Moderate	>1 Ci	1 mCi–1 Ci	10μCi–1 mCi	0–10 μCi
Slight	>10 Ci	10 mCi–10 Ci	100μCi–10 mCi	0–100 μCi

[a]There is an upper limit to the quantity of transuranium elements which should be approved for glove box operations. As a general rule, for those isotopes having a gram HEP index number below 10^{-4}, the limiting quantity should be 100 mg. (For example, 100 mg of Cm-244 generates the same hazard equivalent potential as 4.3 kg of Pu-239.) Any operation involving more than 100 mg of such isotopes should be conducted at facilities with more absolute containment features than are offered by glove boxes alone. This number may require further reduction due to penetrating radiation. One gram of Cf-252, for example, generates a dose rate of 2400 rems/hr at a distance of 1 m in air.

Source: Procedures and Practices for Radiation Protection, Health Physics Manual, Oak Ridge National Laboratory, Oak Ridge, Tenn.

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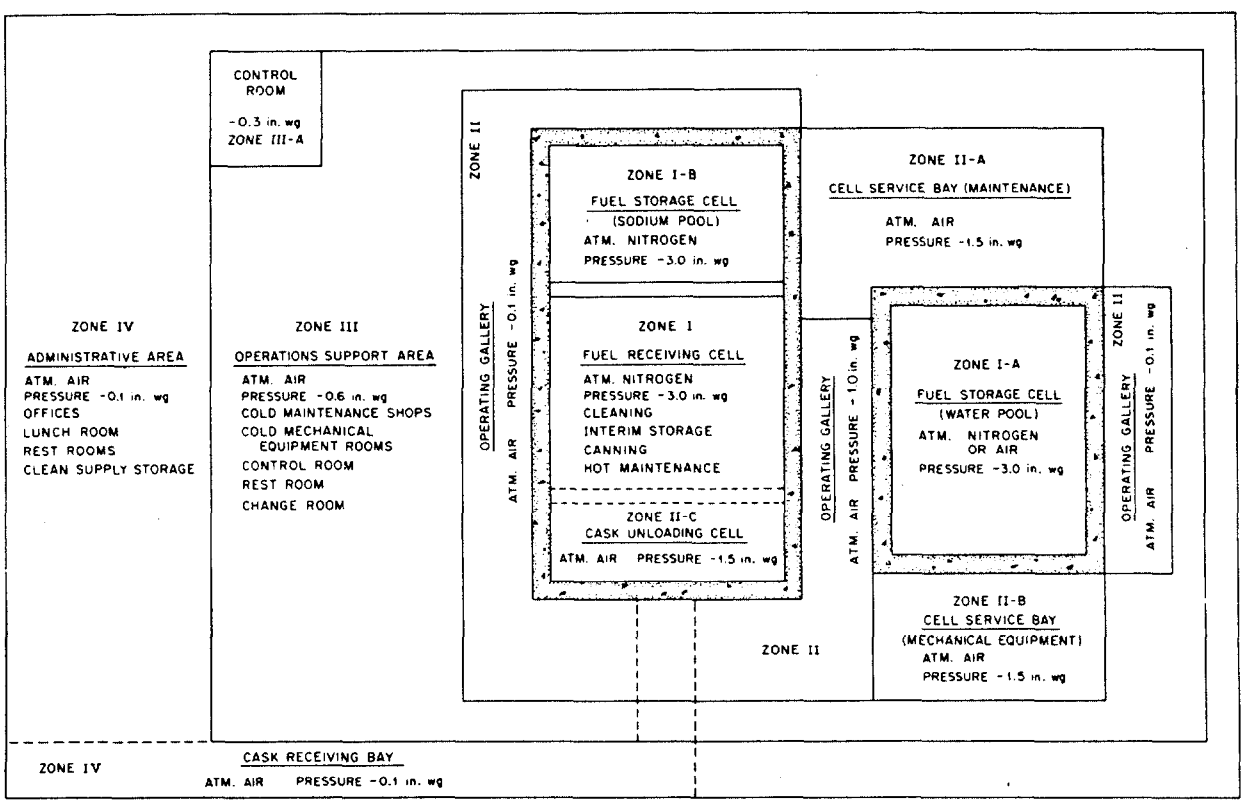

Fig. 2.1. Typical zoning plan for nuclear facility, showing type occupancy and operations permitted and static pressure that must be maintained in each zone to prevent backflow of air to areas of less contamination.

Zone I: The interior of a hot cell, glove box, or other containment for handling highly radioactive material. Containment features must prevent the spread of radioactive material within and release from the building under both normal operating and upset conditions up to and including the design basis accident (DBA) for the facility. Complete isolation (physical separation) from neighboring facilities, laboratories, shop areas, and operating areas necessary. Entry forbidden until area is cleaned up to Zone II classification. Air-exhaust system independent of those serving surrounding areas required. High efficiency filter, preferably HEPA type, required in air inlet; two independently testable stages of HEPA filters required in exhaust. Entry only with full-body protective clothing and with respirators or full-face gas masks, as specified by health physicist.

Zone II: Glove box operating area, hot cell service or maintenance area, or other building space where high levels of radiation could be present. Particularly hazardous operations conducted in chemical fume hoods or glove boxes. Sufficient air supply to produce inward airflow into fume hoods or glove box ports (with glove removed) of at least 100 lin fpm, and may be 200 fpm for particularly hazardous operations or if hot plates, burners, or aspirators are operated within such containment. Air locks or personnel clothing-change facility recommended at entry of zone. Continous monitoring of airborne radioactive material required. Personnel should wear at least laboratory coats and possibly shoe covers in glove box operating areas, and full protective clothing in service areas. Respirators or full-face gas masks should be available in the event of an operational upset. Restricted access areas are generally considered to be Zone II hazard classification.

Zone III: Hot cell operating areas, general chemical laboratories, maintenance, and other general working areas which are usually "cold" but which are subject to low levels of radiation in the air. Chemical fume hoods required for operations which could produce greater than CG for radioactive material or TLV for toxic or noxious material. Operating personnel should wear lab coats or equivalent special clothing, with respiratory gear available for emergencies. Routine airborne radiation monitoring required.

Zone IV: Office and "cold" shop areas. No specific protective clothing requirements. Radiation monitoring may be required at exit points. Bench-top operations permitted in laboratories, but chemical fume hoods should be considered where airborne concentrations could exceed levels stipulated in Table 2.1.

Multizoned buildings are usually ventilated so that airflow is from the less contaminated zone to the more contaminated zone. Recirculation within a zone, with the air circulated through a high-efficiency air cleaning system before discharge back to the zone, might be permitted, but recirculation from a zone of higher contamination back to a zone of lesser contamination is prohibited. The inside of exhaust and recirculating ductwork is considered to be of the same hazard classification as the zone it serves. Airflow must be sufficient to provide the necessary degree of contaminant dilution and cooling and to maintain sufficient pressure differentials between zones where there can be no backflow of air to spaces of lower contamination, even under upset conditions. A pressure differential (Δp) of at least 0.1 in.wg between building zones is recommended, and substantially higher differentials (0.3 to 1.0 in.wg) are often specified between Zone II and Zone I spaces. The following criteria are specified at one of the ERDA national laboratories for the design and operation of radiochemical and laboratory facilities and for the buildings that contain them.[4,5]

Hot cells, caves, and canyons

1. Vacuum equal to or greater than 1 in.wg relative to surrounding spaces shall be maintained at all times to ensure a positive flow of air into the containment.
2. Containment exhaust shall be at least 10% of cell volume per minute to minimize possible explosion hazards due to the presence of volatile solvents and to ensure that, in the event

of cell pressurization due to an explosion, the containment will be returned to normal operating pressure (1 in.wg) in a minimum of time.

3. Maximum permissible leak rate shall be 1% of cell volume per minute for unlined cells, and 0.1% of cell volume per minute for lined and sealed cells at a Δp of 2 in.wg to ensure that the escape of radioactive material will be minimized in the event of cell pressurization; maximum permissible leak rate of ductwork is 0.1% of duct volume per minute at Δp equal to 1.5 times the static pressure of ductwork.

4. Seals and doors shall withstand a Δp of at least 10 in.wg to ensure integrity of closures and penetrations under all operating and design basis upset conditions.

5. The containment structure shall withstand the DBA for that facility without structural damage or loss of function.

6. Operating procedures shall be designed to limit quantities of flammable and smoke-producing materials and solvents within limits that can be accommodated by the ventilation system without endangering functionability of the air cleaning facility.

Glove boxes

1. Vacuum shall be at least 0.3 in.wg between the glove box and surrounding room.

2. Exhaust rate is not specified but must be adequate for heat load and dilution requirements of operations conducted in the glove box.

3. Airflow shall be sufficient to provide at least 5 scfm to the glove box and to maintain an inward velocity of at least 100 lin fpm through one open glove port in every five glove boxes in the system to ensure adequate inflow to prevent the escape of contamination in the event of glove failure.

4. Individual glove boxes shall be isolated or isolable (under upset conditions) to prevent spread of fire from one box to another.

Chemical fume hoods

1. Vacuum shall be at least 0.1 in.wg between the laboratory in which the fume hood is installed and the corridor from which the laboratory is entered.

2. Exhaust rate of the fume hood shall be sufficient to maintain sufficient airflow face velocity into the hood to prevent eduction of fumes from the hood to the room, even when the operator walks rapidly back and forth in front of, and close to, the hood face. A face velocity of at least 100 lin fpm is recommended for operations with radioactive materials; 150 fpm is desirable.

3. Each hood in the laboratory should be isolable by means of dampers to prevent backflow through a hood when it is not in service.

4. Each hood used for handling radioactive materials should have a HEPA filter in its exhaust duct, located close to the duct entrance. All hoods should, where practicable, exhaust to a common stack.

5. Hoods should operate on a once-through mode with no recirculation to the room. (This requirement may be reexamined in light of current energy conservation objectives; if a recirculatory system is considered, the air cleaning system must be such that there is no possibility of releasing radioactive or toxic particulates, fumes, or gases to the room, even under the worst foreseeable operating or accident conditions.)

Secondary containment structure or building

1. The building (structure) shall be designed to prevent the dispersal of airborne contamination to the environment in the event of an accident in a hot cell, glove box, fume hood, or building space.

2. Under emergency conditions the building shall be capable of being maintained at a vacuum of at least 0.3 in.wg relative to the atmosphere. For increased reliability and simplicity, some buildings are held at this pressure under normal operating conditions; if this is not practicable, the ventilation system must be capable of reducing building static pressure to 0.3 in.wg in 20 sec or less. All building air shall be exhausted through at least one stage of HEPA filters. During an emergency, the differential between Zone I spaces (glove boxes, hot cells) and other building spaces must also be maintained.

3. Airflow within the building must be from areas of less contamination to areas of higher (or potentially higher) contamination.

4. Recirculation of air within the same zone or room is permitted, but recirculation from the central exhaust system is prohibited.

Air handling system

1. Ventilation (recirculating or exhaust) and off-gas systems shall be backed up by redundant air cleaning facilities (including filters and fans) to maintain containment in the event of fan breakdown, filter failure, power outage, or other operational upset. Airflow shall always be from the less hazardous to the more hazardous area under both normal and upset conditions.

2. Air exhausted from occupied or occasionally occupied areas shall be passed through prefilters and at least one stage of HEPA filters. Contaminated and potentially contaminated air exhausted from a hot cell, cave, canyon, glove box, or other primary containment structure or vessel shall be passed through at least two individually testable stages of HEPA filters in series, plus prefilters, adsorbers, scrubbers, or other air cleaning facilities as required by the particular application. Air that is normally clean but has the potential of becoming contaminated in the event of an operational upset (e.g., exhaust from a Zone II operating area) or during service operations when the zone is opened to a zone of higher contamination (e.g., a hot cell service area) and air from a potentially mildly contaminated space (e.g., Zone III area) require only one stage of HEPA filters in the exhaust.

3. Corrodents or moisture in the exhaust capable of damaging or unduly loading the HEPA filters (or other components, such as adsorbers) shall be removed or neutralized before they can reach components that can be affected.

4. HEPA filters and adsorbers (where required) shall be tested in place at a prescribed frequency (usually twice per year). HEPA filter stages shall exhibit a DF of no less than 3333 (99.97% efficiency) as determined by an in-place test (see Chap. 8); because of the sensitivity of the test, some facilities now specify a minimum DF equivalent to the predelivery test efficiency of the filters (as determined by the manufacturer or ERDA Quality Assurance Station); that is, a DF of 10,000 for the in-place test may be specified where filters having a predelivery test efficiency of 99.99% (which is common today) are used in the system.

Concentration limits for radioactive substances in air are specified in 10 CFR 20.[1] Threshold limit values (TLV) of toxic and noxious substances, including irritant and nuisance substances, are specified in Title 29 of the *Code of Federal Regulations* (Labor) but are more conveniently tabulated by the American Conference of Governmental Industrial Hygienists in the annual issue of TLVs.[6] The latter gives a procedure for determining TLVs for mixed toxicants and also gives limit values for heat stress, nonionizing radiation, and noise.

2.2.2 Airborne Particulates and Gases

Although process-generated dust and particulate matter are the primary reason for installing exhaust or air cleanup filters, a major portion of the dust and particulate matter collected in those filters actually consists of atmospheric dust brought into the building with the supply air or by infiltration and of "people-generated" particulates (e.g., lint, skin, and hair). These particulates contribute to degradation of the filters and sometimes become radioactive when exposed to certain operating environments (e.g., by adsorption of radioactive vapors or gases or by agglomeration with already radioactive particles). Because particles in the size range of 0.05 to 5 μm tend to be retained by the lungs when inhaled, they are of primary concern in operations that involve radioactive material;[7] they are also recognized as health hazards of nonradioactive air pollution.[8] As Table 2.4 shows, over 99% of the actual number of particles present in atmospheric air falls in this size range.

Reports of dust concentration in air are generally based on the mass of particulate matter present. As Table 2.4 shows, mass accounts for only a negligible portion of the total number of particles in the air. This is important in filter selection because it indicates that some filters that have high efficiency based on weight may be inefficient on a true count basis. That is, they are efficient for large particles but inefficient for small (>0.75 μm) particles. This is true of most common air filters used as prefilters. The HEPA filter, on the other hand, is highly efficient for all particle sizes, down to and including the smallest shown in Table 2.4. The 99.97% minimum efficiency claimed for these filters is actually for the most penetrating size particles, those in the range from 0.07 to 0.3 μm. Dust concentrations vary widely from place to place and, for the same location, from season to season and from time to time during the same day. Concentrations in the atmosphere may vary from as low as 0.01 grain per 1000 ft^3 in rural areas to more

Table 2.4. Distribution of particles in typical urban air sample

Mean particle size (μm)	Particle size range (μm)	Approximate particle count per cubic foot of air	Percent by weight	Percent by count
20.0	50 – 10	12.5×10^3	28	1×10^{-10}
7.5	10 – 5	10×10^4	63	8×10^{-10}
2.5	5 – 1	12.5×10^6	6	1×10^{-7}
0.75	1 – 0.5	10×10^7	2	8×10^{-7}
0.25	0.5 – 0.1	12.5×10^9	1	1×10^{-4}
0.05	0.1 – 0.001	12.5×10^{15}	<1	99.9999

Source: From the Frank Chart, American Air Filter Co., Louisville, Ky.

than 10 grains per 1000 ft^3 in heavily industrialized areas. Dust-producing operations may generate concentrations as great as several thousand grains per 1000 ft^3 at the work place. Because the weight percent determinations on which these concentrations are based account for only a small fraction of the number of particles present, the true count of particles smaller than 5 μm may number in the billions per 1000 ft^3. Atmospheric dust concentrations are usually lowest during the summer months (June 1 to August 1)—as much as 30% lower at that time than during the remainder of the year.[9] Filter selection, particularly prefilter selection and building supply filter selection, must take into consideration the atmospheric dust concentrations that can be encountered at the particular site at any time of the year.

Description	Appearance	Kinds	Percent Present by Weight: Range	Percent Present by Weight: Average
Spherical		Smokes, Pollens, Fly ash	0–20	10
Irregular cubic		Minerals, Cinder	10–90	40
Flakes		Minerals, Epidermis	0–10	5
Fibrous		Lint, Plant fibers	3–35	10
Condensation flocs		Carbon, Smokes, Fumes	0–40	15

Fig. 2.2. Distribution of airborne particulates in the atmosphere, by particle shape. From K. T. Whitby; see ref. 9.

Figure 2.2 shows the distribution of particles (by weight percent) in atmospheric air as a function of particle shape. Variations in particle shape, mean particle size, particle size range, and concentration affect filter life, maintenance costs, and operational effectiveness. The size range of various types of particles, the technical nomenclature of various types of aerosols, and the applicability of various types of air cleaning devices as a function of particle size are shown in Fig. 2.3. A major source of the lint often found on filters is derived from the abrasion of clothing as people move about. In addition, a person at rest gives off more than 2.5 million particles (skin, hair, etc.) and moisture droplets per minute, in the size range of 0.3 μm to 1 μm.[10] Process-generated aerosols fall into two general size ranges. Those produced by machining, grinding, polishing, and other mechanical operations are generally large, probably from 1 μm to several hundred micrometers, according to the nature of the process, and can be removed effectively by common air filters or other conventional air cleaning techniques. The other class includes those produced by evaporation/condensation and other chemical operations, which generate droplets and solid particles that are often in the submicron size range. These aerosols are more difficult to separate from air or gases, and recourse must be made to collectors such as HEPA filters. Other process-generated contaminants include radioactive halogen and noble gases. Because of their chemical inertness, limited reactivity with available sorbents, and great difficulty of separation, the noble gases (xenon and krypton) were treated in the past by simple holdup, to give time for radioactive decay of the shorter half-life elements, and dilution before discharge to the atmosphere. Newer practice, particularly in view of ALARA requirements, is to separate the noble gases by cryogenic fractionation, charcoal adsorption, or fluorocarbon absorption, and store them until a significant degree of radioactive decay can take place. The halogen gases, essentially elemental iodine and certain organic iodides, constitute the largest fraction of the gaseous effluents and are captured by adsorption on activated carbon or certain synthetic zeolites.

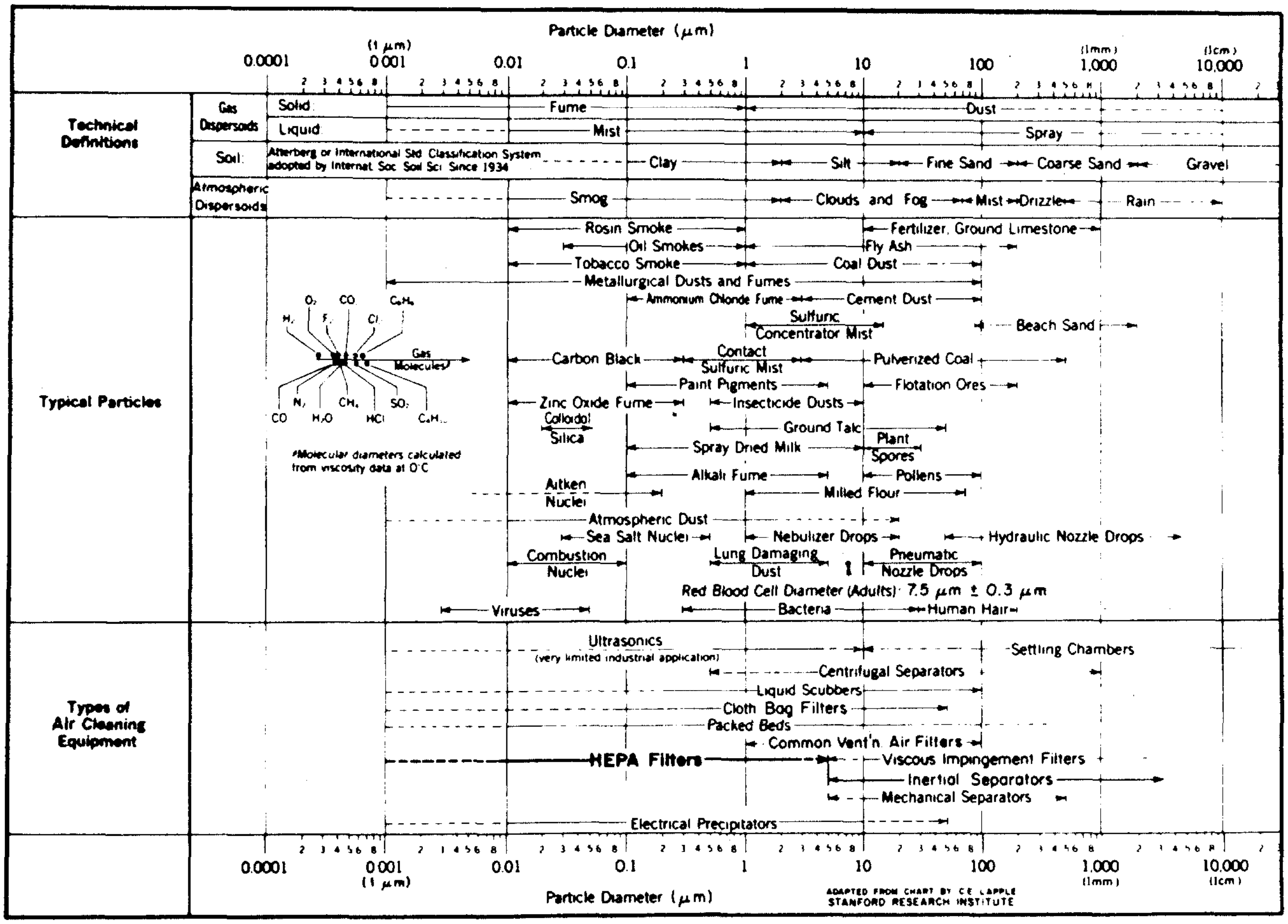

Fig. 2.3. Characteristics of atmospheric and process-generated particulates, fumes, and mists and effective ranges of typical air cleaning equipment. Solid line indicates range of normal application. Courtesy C. E. Lapple, Stanford Research Institute.

2.2.3 Moisture

Sensible moisture in the air is a hazard to prefilters, HEPA filters, and adsorbents. Where heavy concentrations of water mist or steam can be expected, under either normal or upset conditions, heaters, demisters, or other means of reducing entrained moisture to tolerable levels must be provided upstream of the filters to prevent plugging, deterioration, and reduced performance. Condensation from saturated air or gas streams and carry-over from air washers and scrubbers are common sources of sensible moisture. When fire-protection sprinklers are provided in operating areas or ducts, moisture can be drawn into the filters if they are activated in the event of a fire. In nuclear reactors, large volumes of steam and moisture would be expected in the very unlikely event of a major loss-of-coolant accident or heat-exchanger failure; this moisture can impair the performance and integrity of HEPA filters and adsorbers unless removed before reaching those components.

Condensation is particularly troublesome when filters are installed in underground pits, in housings located outdoors, or in unheated spaces of buildings. Even when air entering ducts is above the dew point, duct walls, dampers, or filters may be cold enough to cause condensation on their surfaces. Condensation can also take place in standby systems, particularly when groundwater can evaporate into the filter housing to condense on the walls, mounting frames, or filters; salts that leach from wood filter casings can rapidly deteriorate aluminum separators. In one instance, the separators of a bank of HEPA filters were nearly destroyed by this action in a three-month period. Periodic ventilation of standby filters, on a monthly or even weekly basis, is recommended to prevent such occurrences.

2.2.4 Heat and Hot Air

Continuous operation at high temperature (>200° F) may be detrimental to both HEPA filters and activated-carbon-filled adsorbers. At high temperatures, the shear strength of adhesives used in the manufacture of HEPA filters and some prefilters diminishes, thereby limiting the safe pressure drop to which they can be subjected. The limiting temperature varies with the specific adhesive used and should be checked with the filter manufacturer where operation at elevated temperatures is considered.[11] Limiting temperatures for HEPA filters are given in Chap. 3. For continued operation at temperatures in excess of 200° F, a specially constructed HEPA filter, in which the filter core is sealed into the steel case by means of a compressed mat of glass fibers, is generally employed; however, tests show that the efficiency of these filters, when operating at high temperatures (about 800° F), decreases substantially below the specified value of 99.97% minimum number efficiency for submicron particles, even though the filters purportedly operated within that specification value when tested at room temperature before and after the high temperature runs.[12] Apparently the steel case sides expand away from the filter core, thus permitting some degree of bypassing at high temperature. Most commercially available prefilters are not resistant to heat, and special constructions must be specified if continuous operating temperatures exceed 200° F.

Ceramic-fiber filters having efficiencies as high as 80% for 0.3-μm particles are suitable for service at temperatures up to 2000° F. As with other types of HEPA filters, however, DOP efficiency tests have been made only at room temperature, and the actual efficiency at high temperature is unknown. Ceramic-fiber filters are very expensive, extremely fragile, and must be handled and installed with great care.

The limiting temperature of adsorbents for capturing radioactive iodine and iodine compounds is related to the desorption temperature of the adsorbed compound and of the impregnants with which the material has been treated to enhance its adsorption of organic radioiodides. For triethylene diamine (TEDA) impregnated activated carbon, this temperature may be as low as 300 to 350° F.

When temperatures higher than the operating limits of air cleaning system components must be accommodated, heat sinks, dilution with cooler air, or some other means of cooling must be provided to reduce temperatures to levels that those components can tolerate. Consideration must also be given to thermal expansion and heat resistance of ducts, dampers, filter housings, component mounting frames and clamping devices, and fans. Consideration must also be given to flammability of dust collected in the ducts and on the filters.

2.2.5 Corrosion

Many radiochemical operations generate acid or caustic fumes that can damage or destroy filters, other system components, and materials of construction. High levels of system performance and reliability cannot be ensured when filters are exposed, even occasionally, to corrosive fumes unless corrosion-resistant HEPA filters, with specially treated media and separators and wood cases, and stainless steel ducts, housings, and mounting frames are employed. A new hydrogen fluoride resistant HEPA filter medium has been developed;[13] however, the material has not yet been produced commercially. Although stainless steel filter cases have sometimes been employed for corrosion resistance, this is false economy because the life of standard case materials is nearly always greater than the life of the filter core. Stainless steel should not be specified for HEPA filter separators because it makes the filter core impossible to fabricate; separatorless filters, corrosion-resistant asbestos separators, or even plastic-coated aluminum separators are recommended.

Stainless steel is recommended for ductwork and housings when corrosion can be expected. Even this material may be insufficient in some cases, and coated (e.g., vinyl, epoxy) stainless steel or fiber-reinforced plastics may be necessary (corrosion-resistant coatings are covered by ANSI N512);[14] plastics must be used with caution because they will soften and may collapse if exposed to high temperatures, as might be encountered during a fire in the workroom.

Scrubbers or air washers may be employed to pretreat the air or gas before it enters the final filters, but consideration must also be given to moisture carry-over if the scrubbers or airwashers are not designed and operated properly. Demisters should be provided ahead of the filters. Corrosion is always a danger but is not always obvious. In activated-carbon-filled adsorbers, for example, even trace amounts of NO_2 or SO_2 will concentrate in the adsorbent over a period of time; in the presence of moisture, they can form nitric or sulfuric acids that are capable of corroding metal parts of the adsorber. In one instance, this sequence of events required replacement of several hundred carbon-steel-cased adsorber cells with stainless steel units, at a very substantial cost. Aluminum and carbon steel are subject to corrosion when in contact with moisture-laden carbon. For this reason, stainless steel is always recommended for adsorber cells and for adsorber-cell mounting frames.

2.2.6 Vibration

Vibration and pulsation can be produced in an air or gas cleaning installation by turbulence generated in poorly designed ducts, transitions, dampers, and fan inlets and by improperly installed or balanced fans and motors. Apart from discomfort to personnel, excessive vibration or pulsation can result in eventual mechanical damage to system components when vibrational forces become high or when accelerative forces (e.g., from an earthquake or tornado) coincide with the resonant frequencies of those components. Weld cracks in ducts, housings, and component mounting frames may be produced by even low-level local vibration if sustained, and vibrations or pulsations that produce no apparent short-term effects may cause serious damage after long duration.

Vibration produces noise that can range from the unpleasant to the intolerable. An important factor in the prevention of excessive vibration and noise is planning at the stage of initial building layout and space allocation to ensure that adequate space is provided for good aerodynamic design of ductwork and fan connections. Spatial conflicts with the process and with piping, electrical, and architectural requirements should also be resolved during early design so that the compromises that are so often made during construction, which lead to poor duct layout and resultant noise and vibration, can be avoided. Ducts should be sized to avoid excessive velocities while maintaining the necessary transport velocities to prevent the settling out of particulate matter during operation. Fan vibration can be minimized through the use of vibration isolators and inertial mountings, although the use of these must be balanced against seismic design requirements where necessary (some designers prefer hard-mounting of fans where continued operation during and after an earthquake must be considered). Flexible connections between the fan and ductwork are often employed, but these must be designed to resist the high static pressures often incurred in this class of system, particularly in those parts of the system which are under negative pressure. Finally, the ductwork system must be balanced after installation, not only to ensure the desired airflows and resistances, but to "tune out" any objectionable noise or vibration that may have been inadvertently introduced during construction.

2.3 OPERATIONAL CONSIDERATIONS

2.3.1 Operating Mode

According to operational requirements, an air cleaning system may be operated full-time, part-time, or simply held in standby for emergency service. If processes in the building are operated only one or two shifts a day, the designer may have a choice between continuous operation and operation only during those shifts. He must evaluate the effects of daily starts and stops on the performance and life of filters and other components vs the higher power and maintenance costs that may be incurred by continuous operation. Experience has shown that, all factors considered, continuous operation of air cleaning facilities, perhaps at reduced flow during weekends and holidays, is generally the most satisfactory mode of operation for buildings in which radioactive operations are conducted. Unless ducts, filter housings, damper frames, and fan housings (i.e., the pressure boundary) are extremely leaktight, outleakage of contaminated dust into occupied spaces of the building may occur during shutdown periods.

Many facilities require standby exhaust or air cleanup systems that are operated only in the event of an emergency or redundant air cleaning facilities that are brought into operation when a parallel on-line facility is shut down because of failure or for maintenance. When designing standby systems, the engineer must keep in mind the possibility of corrosion and filter and adsorber deterioration even when the system is not in use.

2.3.2 Filter Change Frequency

The principal costs in operating a high-efficiency air cleaning system are power (i.e., for fans), replacement filters and adsorbers, and labor. The principal factor that affects these costs is the frequency of changing filters (adsorbers). Replacement filters and adsorbers and labor costs may make up as much as 70% of the total cost of owning a system (including capital costs) over a 20-year period. Power accounted for only 15% of the total owning costs in a study made by the Harvard Air Cleaning Laboratory.[15] Measures such as the use of high-efficiency building supply-air filters, the use of prefilters ahead of HEPA filters, operation of the system below its rated airflow capacity, and operation of HEPA filters until they have reached high airflow resistance before replacement all tend to decrease filter change frequency and thereby reduce costs. These factors are discussed in the following sections.

2.3.3 Building Supply-Air Filters

Atmospheric dust brought into the building with ventilation air constitutes a substantial fraction of the dirt load in the building and the dust load in the exhaust air cleaning system. Removal of this dust before it gets inside the building has the double advantage of protecting the exhaust filters from premature dust loading and of reducing janitorial and building maintenance costs. When operations within a building do not generate heavy concentrations of smoke, dust, or lint, it may be possible, by providing medium-efficiency (50 to 65% ASHRAE efficiency)[16] building supply-air filters, to substantially reduce the dust loading in the exhaust system, thereby shifting much of the burden of what would otherwise be a change of "hot" (radioactive) prefilters in the exhaust system to a more economical change of "cold" supply-air filters. The labor costs involved in replacing "cold" filters is a small fraction of those for replacing "hot" filters.

Noticeable reductions in janitorial costs have been observed in several ERDA installations after changing to higher efficiency building supply-air filters. There is also a trend toward using better building supply-air filters in commercial buildings; one operator of a commercial office building reported that the time interval between major cleaning and repainting had doubled after replacing his original panel-type furnace filters with 60% ASHRAE-efficiency filters.[17]

Louvers or moisture separators or both must be provided at the air inlet to protect the supply filters from the weather. Rain, sleet, snow, and ice can damage or plug building supply-air filters, resulting not only in increased operating costs but upset of pressure conditions within the building and possible impairment of the more critical exhaust air cleaning system. Heaters are desirable in the building supply system, even in warm climates. Icing has caused severe damage to building supply-air filters at a number of ERDA installations, even in the South. Screens should be provided over supply-air inlets located at ground or roof level to protect inlet filters and demisters from grass clippings, leaves, dirt, and windblown trash. If possible, inlets should be located well above grade or adjacent roofs so they are not burdened by such materials, preferably at the second-floor level (or equivalent height above an adjacent roof) or higher.

2.3.4 Prefilters

HEPA filters are intended primarily for removal of submicron particles and should not be used as coarse-dust collectors. They have relatively low dust-holding capacity, particularly for large particles and lint, and may plug rapidly when exposed to high concentrations of such material or smoke; lint may tend to bridge the pleats of the filter, even further reducing its capacity. The HEPA filter is also the most critical particulate-removal element in the air cleaning system from the standpoint of preserving containment, and its failure will result in a failure of system function. Prefilters, installed either locally at the entrances to intake ducts, in the central exhaust filter house, or both, extend the life of HEPA filters and provide at least a measure of protection against damage. Local duct-entrance filters also minimize dust accumulation in ducts and reduce an otherwise potential fire hazard. A typical increase in HEPA filter life through the use of prefilters is illustrated in Fig. 2.4. The increase for a specific application is, of course, dependent on the quality of the prefilter selected and the nature and concentration of dusts and particulate matter in the system.

Generally, prefilters should be provided when the potential dust concentration in the air leading to the air cleaning system exceeds 10 grains per 1000 ft^3 and should be considered if the dust concentration exceeds 1 grain per 1000 ft^3. The use of prefilters is recommended in engineered safety feature (ESF) systems for nuclear reactors.[18] The decision to install prefilters should be based on providing the best operational balance between HEPA filter life, with its attendant decrease in HEPA filter change frequency, and procurement and maintenance costs for the prefilters.

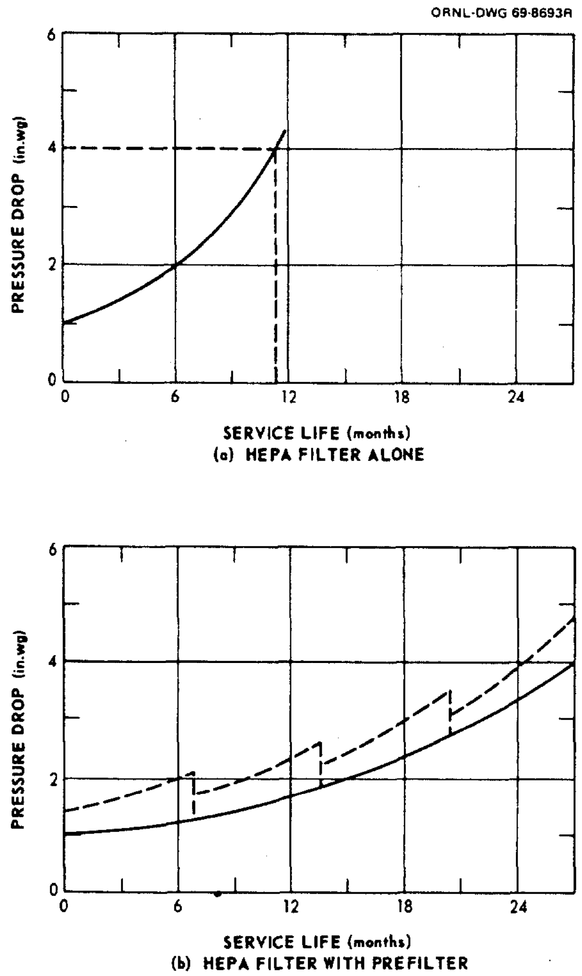

Fig. 2.4. Comparison of HEPA filter life with and without prefilter. HEPA filter replaced at 4 in.wg pressure drop and prefilter replaced when pressure drop across it reaches twice the clean-filter pressure drop. From P.A.F. White and S. E. Smith, eds., *High Efficiency Air Filtration*, Butterworth & Co., London, 1964.

Duct-entrance prefilters can be changed without entering or interrupting the central air cleaning facility, can minimize dust buildup in the ducts, and can provide a measure of protection against duct corrosion, accidental high-moisture loadings, and flaming trash or sparks that may be produced by a fire in the working space. On the other hand, a system that has a number of local prefilter installations may cost from two to three times as much as one in which the same prefilter capacity is installed in a central housing.[15]

Prefilters in a central air cleaning system should not be attached directly to or installed back-to-back to HEPA filters; they should be installed on a separate mounting frame located at least 4 to 5 ft upstream of the HEPA filters. This installation requires more building space and higher investment costs (particularly when building space is at a premium), but it is justified by increased safety and greater system reliability. Adequate space between prefilters and HEPA filters is needed for access and maintenance and to minimize the propagation of fire by sparks or direct flame impingement. If the possibility of fire is a serious consideration, a removable screen, fine enough to stop sparks (10 to 20 mesh), may be installed on the downstream side of the prefilters.

2.3.5 Operation to High Pressure Drop

Most HEPA filter manufacturers' literature suggests the replacement of HEPA filters when the resistance due to dust loading has reached 2 in.wg. However, HEPA filters, by specification, are capable of withstanding a pressure drop, when clean, of at least 10 in.wg without structural damage or reduction of efficiency[19] (see Chap. 3). Replacement at a pressure drop of only 2 in.wg, when other factors such as radioactivity and fan capacity do not have to be considered, is underutilization of the filter. At many ERDA facilities, HEPA filters are operated routinely to pressure drops as high as 4 to 5 in.wg. Figure 2.5 shows the effect of such operation on filter life and maintenance costs.

The advantages of operating to high pressure drop must be weighed against first cost (higher-static-pressure fans, larger motors, and heavier ductwork), higher power costs, and less efficient fan operation. The installed fan and motor must have sufficient capacity to deliver the design airflow at the maximum differential pressure to which the system will operate, with the filters at maximum dirty-filter pressure drop prior to change. Consideration must therefore be given not only to the increased installed capacity required to operate to the higher pressure drop, but also to the fact that the fan operates at a penalty for much of the time to provide the required airflow over the wide span of pressure drop between installation and replacement of filters.

The cost of ductwork, on the other hand, may not be significantly affected by operation to a high pressure drop because there is a minimum sheet-metal thickness (18 gage recommended for shop operations, 16 gage for field operations) for effective welding, regardless of pressure requirements (see Chap. 5). The cost of fans and motors is a function of

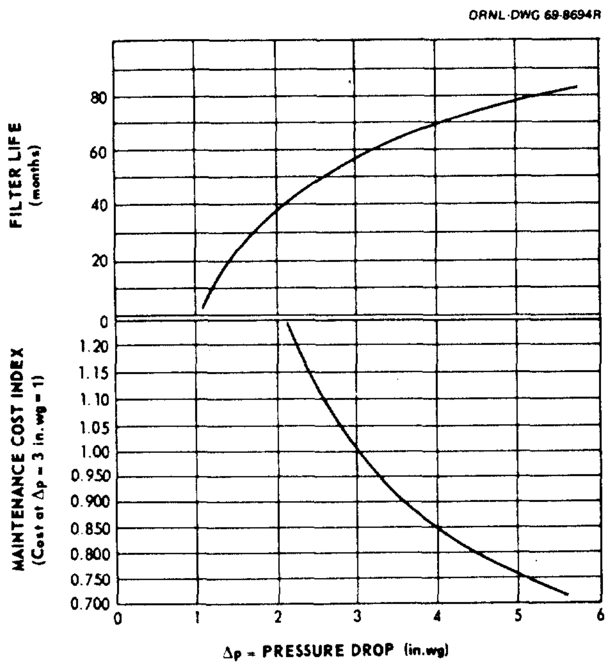

Fig. 2.5. Effect of operating HEPA filters to high pressure drop on filter life and maintenance cost (including replacement filters and labor). From W. V. Thompson, *High Efficiency Particulate Filter History and Activities as of August, 1964, 117-B, C, DR, F, H, KE, and KW Buildings*, USAEC Report RL-REA-1000, Hanford Atomic Products Operation, April 12, 1965.

the maximum total pressure that must be developed. Fan horsepower can be estimated from the equation [20]

$$\mathrm{hp}_f = \frac{Q\,\Delta p}{6356 E_f}\,, \tag{2.1}$$

where

hp_f = fan horsepower,
Q = system airflow, cfm,
Δp = maximum pressure drop across air cleaning system, in.wg, at time of filter replacement,
E_f = fractional efficiency of fan (0.60 usually assumed for estimating).

Motor horsepower can be estimated from the equation [20]

$$\mathrm{hp}_m = \frac{\mathrm{hp}_f}{E_m}\,, \tag{2.2}$$

where

hp_m = motor horsepower,
hp_f = fan horsepower,
E_m = fractional motor efficiency (0.90 usually assumed for estimating for 20-hp motors and larger).

Annual power costs can be estimated from the equation [20]

$$C = \frac{Q\,\Delta p\,hr}{8520 E'_f E'_m}\,, \tag{2.3}$$

where

C = annual power cost, dollars,
h = hours of operation per year,
r = cost of power, cents/kWhr,
E'_f and E'_m = efficiency of fan and motor, respectively, over the period of operation from filter installation to replacement; these will be less than the design efficiencies.

Although investment and power costs will be lower for the system operated to 2 in.wg pressure drop, the total annual cost of owning the system, including materials and labor costs for filter replacement, may be less for the system in which HEPA filters are replaced at pressure drops on the order of 4 to 5 in.wg. Total savings for the facility as a whole may be even greater when the reduced interruption of building operations due to the reduced frequency of filter change is taken into consideration.

Some prefilters can be operated to higher pressure drops than recommended by their manufacturers. In Great Britain prefilters are commonly operated to dirty-filter pressure drops of 3 to 4 in.wg.[21] This results in less frequent prefilter change than if the prefilters are changed at a pressure drop of only two or three times the clean-filter pressure drop (usually 0.1 to 0.5 in.wg) recommended by most manufacturers. Care must be taken in the selection of prefilters. Because of the many types, efficiencies, configurations, and constructions available, the designer must specifically investigate the safe overpressure allowance for the particular model under consideration. Figure 2.6 shows clearly the results of overpressuring prefilters. In this case the problem of filter blowout was overcome by working with the manufacturer to reinforce the filter itself. Some benefit could also have been obtained by installing a screen or expanded metal grille on the downstream face of the prefilters against which the filter cores could bear; in any event, screens or grilles would have prevented damage to the HEPA filters when pieces of prefilter struck them.

2.3.6 Underrating

The service of all internal components, except moisture separators, can be extended and system

Fig. 2.6. Result of overpressuring prefilters. Note damage to HEPA filters in rear. Courtesy Union Carbide Corporation, Nuclear Division, Y-12 Plant.

pressure drop for a given level of dust loading can be reduced by underrating—that is, by oversizing the system and installing more filter and adsorber capacity than is required, based on nominal airflow rating of those components, to meet system design airflow needs. Figure 2.7 shows that the increase in filter life obtainable by underrating is roughly proportional to the square root of the degree of underrating. A study by the Harvard Air Cleaning Laboratory suggests that the economic limit of underrating is about 20% (i.e., system design airflow equal to 80% of installed airflow capacity).[15]

Overrating. The operation of a system at airflows greater than the installed airflow capacity of the system should be avoided, particularly in systems with radioiodine adsorbers whose performance is dependent on residence time of air within the adsorbent bed. When airflow rates exceed rated airflow capacity of HEPA filters, filter life decreases more rapidly than the equivalent increase in flow rate, as can be seen from the 120% curve in Fig. 2.7. As noted above, the residence time of contaminant-laden air in adsorber units is inversely related to airflow rate; overrating of these units decreases their ability to trap gaseous contaminants and thereby degrades their function.

2.3.7 Uniformity of Airflow

In large air cleaning systems, because of the stratification of airflow due to poor transitions between ducts and housings or between housings and fans or because of poorly designed housings, filters or adsorbers at the center of a bank may receive higher airflow than those on the periphery of the bank. This not only results in nonuniform dirt loading of filters but may result in excessive penetration of those HEPA filters closer to the air intake if the degree of airflow nonuniformity is great. Figure 2.8 shows that the penetration of HEPA filters by very small particles is directly velocity-dependent and increases significantly at very high airflow rates. Conversely, the penetration of HEPA filters by particles larger than 1 μm may increase at very low flow rates due to the reduction in effectiveness of the impaction mechanism on which trapping of those particles depends. If some filters are operating at very high airflow and some at very low airflow, as could happen in a poorly designed housing and filter bank, it is possible that significant penetration could occur even though the filters are in good condition. Low flow rates improve the efficiency of radioiodine adsorbers, but high flow rates decrease efficiency, as discussed in the previous section. Therefore, significant nonuniformity of airflow through a bank of adsorber cells can reduce the overall efficiency for trapping radioactive gases of interest. Figure 4.28 shows a well-designed duct-to-housing transition

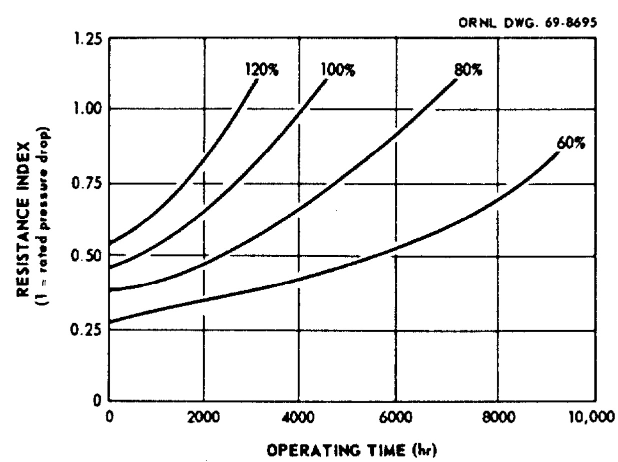

Fig. 2.7. Effect of underrating on service life of extended-medium filters, based on percentage of manufacturer's rated filter airflow capacity. From P. M. Engle and C. J. Bauder, "Characteristics and Application of High Performance Dry Filters," *ASHRAE Journal*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, May 1964, pp. 72–75.

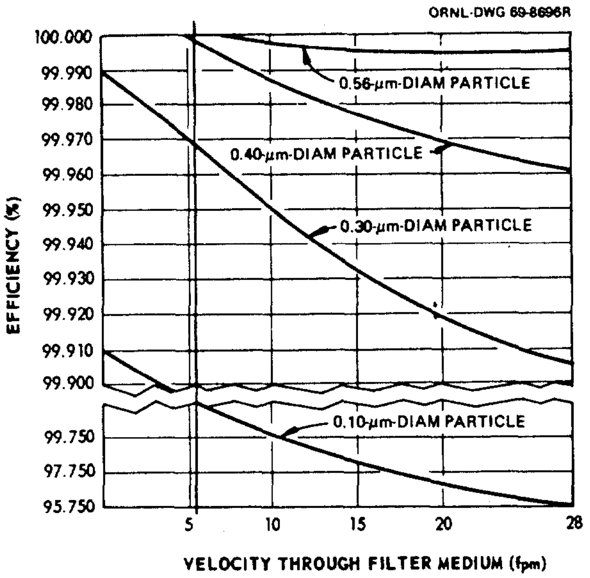

Fig. 2.8. Penetration of HEPA filter medium by submicron particles as function of flow rate through medium. Normal flow rate, at manufacturer's rated filter capacity, is approximately 5 fpm (vertical line). From MSA Ultra-Aire Filters, Bulletin No. 1505-20, Mine Safety Appliances Co.

that will produce satisfactory airflow distribution through the banks of filters and adsorbers.

2.3.8 Maintainability, Testability

Maintenance and testing are two operational factors whose cost can be minimized by good initial design and layout of ventilation and air cleaning facilities. Inadequate attention to maintenance and testing requirements at the initial phase of the project can result in operating costs much higher than they should be. Two elements that largely influence the costs of these functions are the accessibility of components requiring periodic test and service and frequency of filter and adsorber replacement. In systems that involve the handling of radioactively contaminated filters and adsorbers, the frequency of changing these components and the time to accomplish the change can be especially critical, because the total integrated radiation dose a workman can be permitted to receive in each calendar period is limited. When all personnel have received their maximum permissible dose for the period, the supervisor faces the prospect of having no one available to carry out a needed filter change or a scheduled test. Maintenance and testing of radioactively contaminated systems is much more costly than the same operations in nonradioactive systems because of the time required for personnel to change into and out of protective clothing; to decontaminate and clean up the area, tools, and equipment after the operation; to dispose of contaminated filters; and to bathe and be monitored by health physicists. There is also the extra attention that must be given to filter or adsorber cell installation (as compared with common air filters, for example). If the system does not meet test requirements after the change, the work must be repeated. There is also a need for health physics monitoring before, during, and after the operation. The fact that personnel have to work in clumsy protective clothing, including respirator or full-face gas mask, also adds to the time required. Regardless of these inherently high time and money costs, proper maintenance and testing are primary factors in ensuring the reliability of the air cleaning system, and they cannot be done properly unless the physical facilities have been properly designed and built.

Frequency of Maintenance and Testing. All measures that reduce the frequency of filter (HEPA and prefilter) and adsorber replacement also reduce system costs and downtime. Several of the factors discussed earlier—the use of good building supply-air filters and prefilters, operation of HEPA filters to high pressure drop, and underrating—serve to extend component life and reduce the frequency and cost of service. Exhaust system HEPA filter and adsorber installations must be tested after each component change so that any extension of service life also directly reduces testing costs.

Accessibility. When laying out ventilation and air cleaning facilities the designer must consider the location of fans, dampers, instruments, and filter housings and working space adjacent to them; working space and spacing of banks within man-entry housings; height and array of filter and adsorber banks; and routes to be used for moving new and used filters and adsorbers between storage, installation, and disposal areas. Failure to provide adequate space in and around housings and mechanical equipment (fans, dampers, etc.) results in high maintenance and testing costs, inhibits proper care and attention, creates hazards, and increases the chance for the accidental spread of contamination during service or testing operations. Recommendations for the arrangement and space requirements for air cleaning components are given in Chaps. 4, 6, and 7. Even greater space requirements are needed for remotely maintainable systems.

Ease of Maintenance. Simplicity of maintenance and testing is a primary factor in minimizing the time personnel must remain inside a contaminated housing and restricted areas of a building during a filter or adsorber change or test and is, therefore, an important factor in reducing both personnel exposures and costs. Simplicity of maintenance and testing is achievable through the following means:

1. A housing layout that minimizes reaching, stooping, and the use of ladders or temporary scaffolding for gaining access to filter or adsorber cells. Some reaching and stooping are unavoidable in man-entry housings, but it should not be necessary for workmen to go through physical contortions or climb ladders to remove and replace filters in single-filter installations. Similarly, in bank systems it should not be necessary for workmen to climb ladders or temporary scaffolding to gain access to the upper tiers of filters or adsorbers.
2. Adequate finger space (1 in. minimum is desirable) between filter elements and provision of handles on heavy components such as adsorber cells.
3. Cradles or benches built into the component mounting frame for aligning and supporting filters (adsorbers) prior to clamping to face-sealed mounting frames (see Sect. 4.3.5).
4. Simple filter and adsorber clamping devices. A properly designed bolt-and-nut clamping system has proven most satisfactory in the past, although numerous methods of minimizing or eliminating loose parts are currently being investigated. Toggle clamps, over-center latches, and other devices are easily manipulated and require no tools; however, they often tend to jam, become difficult to operate, or lose their ability to properly clamp the filter or adsorber cell after extended exposure to the hostile environment of a contaminated air cleaning system. Such devices should be used only after due consideration of the difficulties that would be involved in replacing them in a contaminated system (see Sect. 4.3.4).
5. Elimination of ledges and sharp corners that a workman might stumble over or might snag or tear his protective clothing on.
6. Adequate lighting in and adjacent to the filter house and adjacent to other items that require periodic service, inspection, or testing.
7. Provision for communication between personnel inside and outside the filter house (e.g., communication ports or portable talker system).
8. Floor drains in housings and adjacent work spaces to facilitate easy removal of water spilled or applied during decontamination of the area after a filter or adsorber change. Drains must be designed so that no air can bypass filters or adsorbers.
9. Availability of electrical, water, and compressed air connections nearby, but in no case inside, the filter house.
10. Materials-handling facilities, including dollies for moving new and used filters and adsorbers, hoists or other means of handling the heavy adsorber cells in systems containing those components, and elevators or ramps for moving loaded dollies up and down within the building.
11. Location of filter housings inside the building. It is undesirable for personnel to (a) conduct a filter change or test out of doors where wind or rain may cause a spread of contamination, (b) cross a roof to gain access to a filter house, or (c) wait for good weather to carry out a scheduled filter or adsorber change or test.
12. Rigid, double-pin-hinged doors on man-entry housings large enough for personnel to pass through without excessive stooping or twisting. It should not be necessary to remove several dozen nuts from a hatch to gain entry to a man-entry or single-filter housing. Not only is this too time consuming, but nuts tend to cross-thread or gall to the extent that it is often necessary to cut off the bolt to open a hatch; or the nuts get dropped and lost and are often not replaced, thus compromising the seal of the hatch. Sliding doors are not suitable because they will jam with any distortion of the housing wall (see Sect. 4.5.7) and are difficult to seal.
13. Nearby decontamination and clothing-change facilities (including showers).
14. Well-planned and rehearsed maintenance and testing procedures.
15. Adequate space for materials and test equipment and access (through preplanned doors or panels) to both sides of filter and adsorber banks.
16. Preplanned test-agent injection ports and sampling ports (see Chap. 8).

Construction. The design for maintainability requires careful attention to details of construction, including tolerances, surface finishes, and the location of adjacent equipment and service lines. Ducts and housings should have a minimum of interior ledges, protrusions, and crevices that can collect dust or moisture or that can impede personnel or create a hazard in the performance of their work. Provision of relatively high efficiency (40 to 65% ASHRAE) prefilters at duct inlets will minimize the accumulation of dust and contamination in the ducts. If these are not provided, easily opened ports and hatches for inspection and cleaning must be provided at strategic and accessible locations in the duct. Duct runs should have enough mechanical joints to permit easy erection and dismantling. Otherwise, replacement of radioactively contaminated ducts can be an expensive and hazardous job.

Housings, ductwork, and component mounting frames must be able to withstand anticipated system pressures and shock loadings without distortion, fatigue, or yielding that permits inleakage or bypassing of the filters or adsorbers. Ability to meet an air pressure test of ±12 in.wg for 1 hr without distortion or excessive leakage (see Table 5.6) is often specified.

Interior surfaces and finishes warrant special attention. Regardless of the formulation when coatings are used, a primary factor in long and dependable service life is proper preparation of the surface to be coated. Coating (or paint) manufacturer's instructions must be followed exactly. All coated or painted metal surfaces that will be exposed to contaminated air and gases should be grit-blasted to white or near-white metal. The first primer coat should be applied as soon as possible, preferably within 4 hr, after completion of grit-blasting. Coatings should be thoroughly cured and ducts and housings completely purged of paint and solvent fumes before installation of adsorber cells or filling of permanent fill-in-place adsorbers.

2.4 SYSTEM CONFIGURATION — NOMENCLATURE

The design, manufacture, installation, testing, operation, and service of nuclear air cleaning facilities involve the efforts of many people of different backgrounds. There has been a tendency on the part of some users to employ different terms for essentially the same items when used in different applications. The result is that similarities of basically similar systems or items are obscured, and experience gained in one situation is not transferred to another. Use of common terminology helps to alleviate this lack of communication. To promote consistency and common understanding, the terms defined in this section are suggested for describing the configuration and arrangement of such systems and their parts.

2.4.1 Component

A component is a filter, adsorber cell, fan, damper, or other basic element of an air cleaning system which cannot be disassembled without nullifying the capability of performing its designed task. Components are often designated by the function they perform (e.g., filter, demister). Items purchased by manufacturer's name and catalog number are generally components. Internal components are normally enclosed within the system or a housing, including such items as filters, demisters, adsorber cells, and heaters. Major internal components are discussed in Chap. 3. External components include those that form part of the pressure boundary of the system and those (such as instruments) that are installed externally to the pressure boundary of the system. Major external components, such as ducts, dampers, fans, and instruments, are discussed in Chap. 5. Housings are discussed in Chaps. 4 and 6.

2.4.2 Air Cleaning Unit

An air cleaning unit is an assembly of components which comprises a single subdivision of a complete air cleaning system, including all components necessary to perform the air cleaning function of that subdivision. Such a unit includes a single-filter housing and its internal components. In a parallel or branched system, the unit includes all components in a single branch of the system. This conforms with the terminology of ANSI N509.

2.4.3 Air Cleaning System

An air cleaning system is an assembly of one or more air cleaning units (see Sect. 2.4.2) plus all external components needed to convey air or gases from one or more intake points, through the air cleaning units, to one or more points of discharge. The system may be either recirculating, in which the cleaned air is returned to the space from which the contaminated air was drawn or to a space subject to greater contamination, or once-through, in which the cleaned air is discharged directly to the atmosphere, for an exhaust system, or to a building space in the case of a supply system.

2.4.4 Ventilation System

The ventilation system includes the total facilities required to supply air to, circulate air within, and remove air from a building or building space by natural or by mechanical means. The ventilation system may or may not include air cleaning, air-conditioning, or heating facilities.

2.4.5 Filter or Adsorber Bank

A filter or adsorber bank is an assembly of two or more internal components of the same kind, in parallel, within the same housing.

2.4.6 Array

An array is the arrangement of internal components in a bank, expressed as the number of components across the width of a bank times the number high (e.g., a 4 by 3 array of HEPA filters).

2.4.7 Air Cleaning Stage

An air cleaning stage is a single component or a bank of identical components in an air cleaning unit or an air cleaning system. A system that has one bank of components (e.g., HEPA filters) in each of three air cleaning units, arranged in parallel, is a single stage system. A multistage unit or system has two or more stages in tandem.

2.4.8 Installed Capacity

Installed capacity is the manufacturer's rated airflow capacity of a bank or stage of the same kind of components, expressed as the number of components (in the bank or stage, respectively) times the rated airflow of the individual components.

2.4.9 Single-Component Air Cleaning Unit

A single-component air cleaning unit is one in which there is only one component (HEPA filter, prefilter, etc.) per stage, as opposed to a bank installation in which there are two or more components per stage.

2.4.10 Single-Path System

A single-path system is one in which the total installed capacity of the air cleaning system is installed in a single air cleaning unit (see Sect. 2.4.2).

2.4.11 Parallel System

A parallel system has two or more air cleaning units in parallel (see Fig. 2.9).

2.4.12 Segmented System

A segmented system is a parallel configuration in which the installed capacity necessary to meet system design airflow requirements has been subdivided into two or more parallel air cleaning units (see Fig. 2.9).

2.4.13 Redundant System

A redundant system is a parallel system (Sect. 2.4.11) that contains one or more independently operable air cleaning units (Sect. 2.4.2) which provides excess system design airflow capacity, either in multiples of the system design airflow capacity or in integral fractions of that capacity (see Fig. 2.9).

2.4.14 Branched System

A branched system is a parallel configuration having a common entrant duct or inlet, a common discharge duct, or both (see Fig. 2.9).

2.4.15 Isolable Unit

An isolable unit is an air cleaning unit which, by means of dampers, backflow preventers (dampers), fan location, or system layout, can be isolated from other units that comprise the system and which can be operated simultaneously with, or alternatively to, the other units that comprise the system.

2.4.16 Compartmented Unit

A compartmented unit is an air cleaning unit in which stages of components are installed in individual compartments in series, as illustrated in Fig. 2.10.

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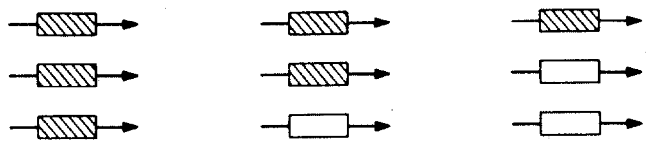
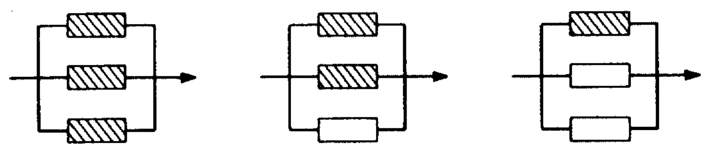


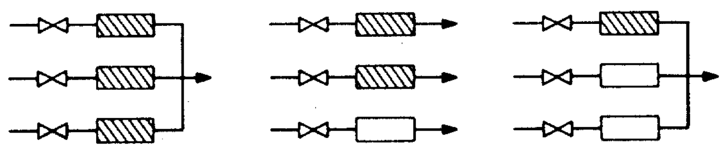
	a	b	c
BRANCHED	NO	NO	NO
SEGMENTED	YES	YES	NO
REDUNDANT	NO	YES	YES
ISOLABLE	YES	YES	YES

2



	a	b	c
BRANCHED	YES	YES	YES
SEGMENTED	YES	YES	YES
REDUNDANT	NO	YES	YES
ISOLABLE	NO	NO	NO

3



	a	b	c
BRANCHED	YES	YES	YES
SEGMENTED	YES	YES	NO
REDUNDANT	NO	YES	YES
ISOLABLE	YES	YES	NO

Fig. 2.9 Properties of some parallel air cleaning system configurations.

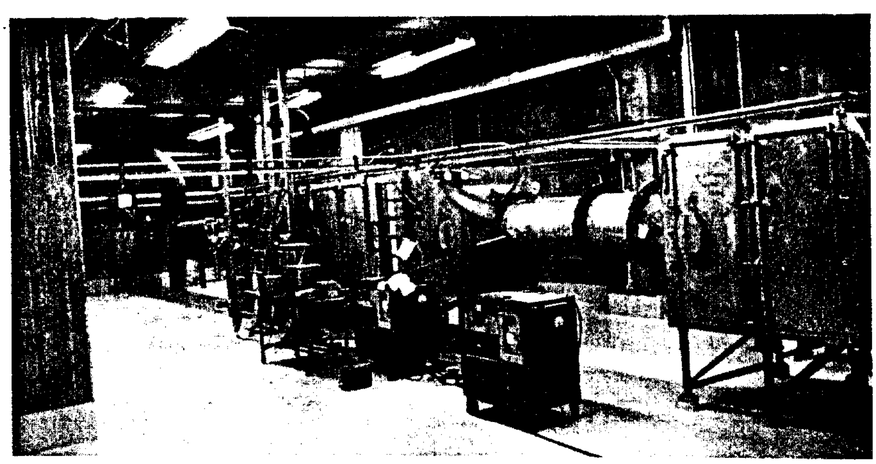


Fig. 2.10. Series-compartmented air cleaning system. Demisters, prefilters, and first-stage HEPA filters are installed in the compartment on the left; adsorber cells and second-stage HEPA filters are installed in the compartment on the right.

2.5 EMERGENCY CONSIDERATIONS

The ventilation and air cleaning systems of a building in which radioactive materials are handled or processed are integral parts of the building's containment. In some cases, these systems may be shut down in the event of an operational upset, power outage, accident, fire, or other emergency; in other cases they must remain operational to maintain the airflows and pressure differentials between building spaces and between the building and the atmosphere, which are needed to maintain containment. In some cases, airborne radioactive material may not be a problem until an emergency occurs. In all of these cases, a particular danger is damage to or failure of the final HEPA filters (and adsorbers in those facilities where radiolytic gases could be released) that constitute the final barrier between the contained space (hot cell, glove box, room, or building) and the atmosphere or adjacent building spaces. Even if the system can be shut down in the event of an emergency, protection of the final filters is essential to prevent the escape of contaminated air to the atmosphere or to occupied spaces of the building.

Some damage to or degradation of the ventilation system, the final filters, or the adsorbers is probably not completely avoidable in the event of a serious incident. Consideration must be given to (1) the possible effects of operational upsets, power outages, accidents, fires, and other emergencies on the ventilation and air cleaning systems, including damage to the filters and adsorbers from shock, overpressure, heat, fire, and high sensible-moisture loading; (2) the design and arrangement of ducts and air cleaning components to alleviate these conditions; (3) means of switching to a redundant air cleaning unit, fan, or alternate power supply; and (4) methods of controlling the exhaust system during failure conditions. To provide the necessary protection to the public and to plant personnel, air cleaning and ventilation system components on which containment leakage-control depends must remain essentially intact and serviceable under the upset conditions. These components must be capable of withstanding the differential pressures, heat, moisture, and stress of the most serious accident predicted for the facility, with minimum damage and loss of integrity, and they must remain operable long enough to satisfy system objectives.

2.5.1 Shock and Overpressure

Mechanical shock in an air cleaning system can be produced by explosion in an operating area of the building, by an earthquake, or by rapid compression or decompression of the air inside a system caused by sudden opening or closing of a damper or housing doors. When pressure transients last for periods measurable in seconds, static pressure is primarily responsible for any destructive effect. For shocks that have a duration of only a few milliseconds with nearly instantaneous pressure rise, as occurs in most chemical explosions, destructiveness is primarily a function of the momentum of the shock wave. Shocks produced by an earthquake or inadvertent opening or closing of a damper usually fall somewhere between these two extremes. Protection of the final filters and adsorbers against failure from shock can be accomplished by isolating them to prevent the transmission of forces to them and by increasing the shock resistance of ducts, housings, mounting frames, and equipment supports. The shock resistance of HEPA filters can be enhanced by face guards (see Sect. 3.2.4),[22] and similar treatment may sometimes improve the shock resistance of prefilters. Most prefilters used today, however, probably have low shock and overpressure resistance, and a screen installed between them and the HEPA filters is recommended to prevent the condition shown in Fig. 2.6. Adsorbers, both unit-tray and permanent single-unit (PSU) types (see Sect. 3.4), are generally of a robust construction that should be relatively unaffected by shock loadings if properly installed. Filter and adsorber mounting frames and housings designed in accordance with recommendations in Chap. 4 will probably have adequate shock resistance for most applications. The difference in the ability of the two fan installations, shown in Fig. 2.11, to withstand a substantial degree of shock is readily apparent.

Protection of the primary air cleaning components can be achieved by providing sharp turns, heavy perforated plates, or cushion chambers in the ductwork to "snub" shock forces and by using fast-acting isolation dampers. Although turning vanes, dampers, moisture separators, and prefilters may be damaged by a shock wave, they may also serve to attenuate its force to some degree and thereby provide a measure of protection to the HEPA filters downstream. Damage to dampers, however, can result in inability to control flows or isolate branch lines. Sand filters are employed in some ERDA facilities for protection of the final filters and to prevent loss of containment in the event of explosion, earthquake, tornado, fire, or shock. As discussed in Chap. 9, sand filters are large deep beds of graded sand and gravel, installed in underground concrete enclosures. In some cases they are employed as final filters. Because their submicron particle-collection efficiency probably does not exceed about 99.7% and because some leakage may occur in the event of an explosion or other shock, they should be backed up by HEPA filters. On the other hand, airflow is upward through the bed, and leakage should be only momentary because of the great mass of sand and gravel comprising the filter and the disposition of the disturbed sand to fall back to heal the breach. This large mass of sand and gravel also provides a substantial heat sink in the event of fire in a ventilated space. The disadvantages of sand filters are very high first cost and high pressure drop.[23]

Explosion in an operating area of a building is probably the most likely type of shock-generating incident that one can expect in radiochemical,

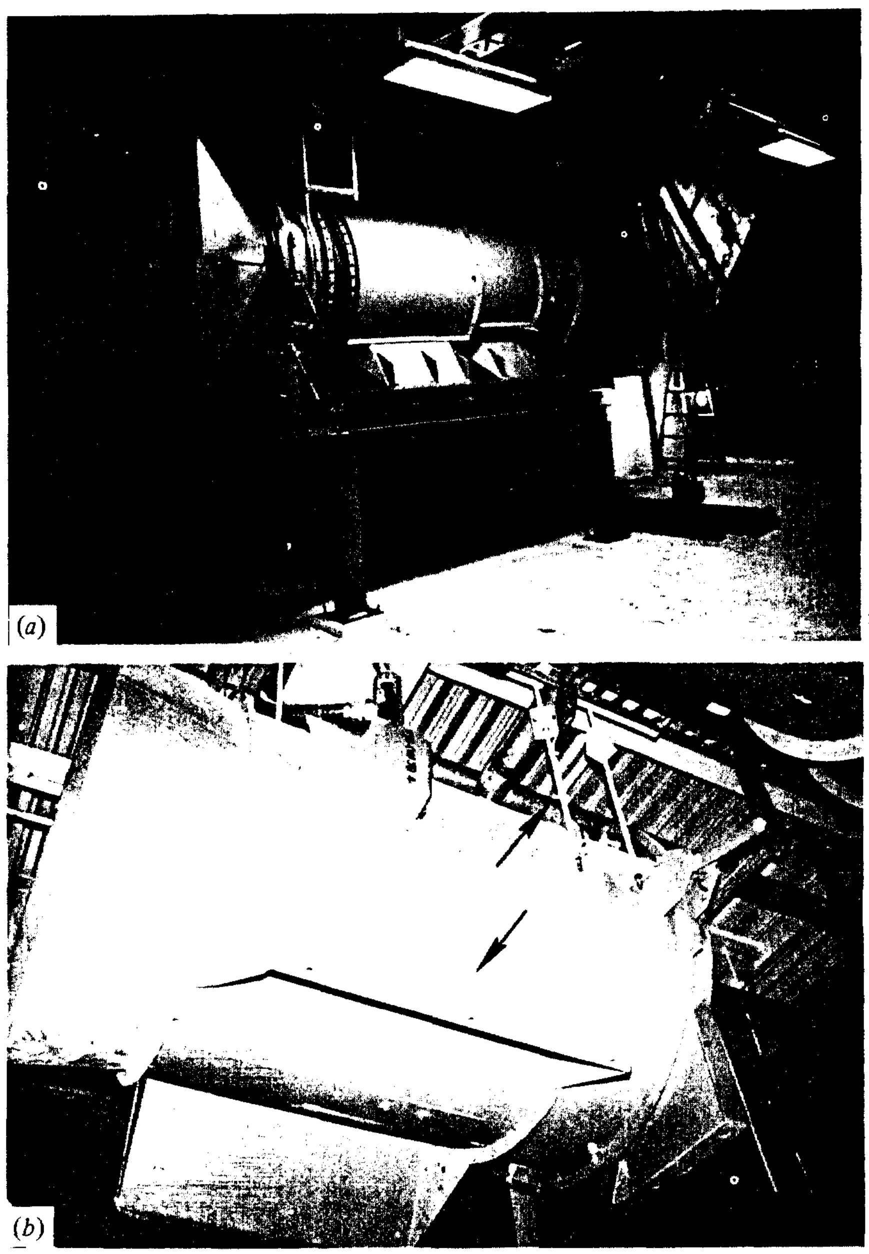


Fig. 2.11. Methods employed for installing axial-centrifugal fans in different nuclear reactor ESF air cleaning systems. (*a*) Shock-resistant base-mounted fan; (*b*) hanger-rod supported fan. Note anchor plates provided by fan manufacturer, but not used.

laboratory, and experimental facilities. A chemical explosion is no more than a rapidly burning fire and therefore, in a confined space, can be arrested if a suppressant can be introduced quickly enough. Fluorocarbon gases such as halon-1301 (bromotrifluoromethane) have been found effective for this purpose in many situations. A concentration of 15 to 20% halon-1301 is required to suppress an explosion, after which a concentration of only 3 to 4% is needed to prevent reignition. In operation, an extremely sensitive pressure-sensor signals an explosive-actuated release valve on the halon cylinder installed in the contained space. Tests have confirmed that an incipient explosion can be suppressed in less than 60 msec with a maximum pressure rise in the contained space (a glove box in the test) of 2 psi.[24,25] Halon-1301 is particularly attractive for glove box and hot cell applications except where pyrophoric metal dusts or chips are being handled.

2.5.2 Fire and Hot Air

Fire in activated-carbon adsorption systems has received considerable attention in the last few years, but the possibility of fire in other components of the air cleaning system, such as ducts and filters, has been largely overlooked, except by the national laboratories and other ERDA prime contractors.[26] Adequate provision for the detection and control of duct and filter fires has been the exception rather than the rule. Fires in glove boxes, hot cells, laboratories, and other nuclear containment facilities pose special difficulties to air cleaning and ventilation systems because of the need to contain airborne radioactive material during the emergency. The release of contaminated smoke through a ruptured HEPA filter or other breach of the containment building may have more serious consequences than any potential casualty losses from the fire itself.

Where it is possible to completely isolate and seal off the contained space within a building in which a fire occurs, or the building itself, including the ventilation system, consideration of effects of the fire on the filters and other air cleaning components may not be so important. In most facilities, however, it is essential to maintain some degree of airflow through the exhaust system in order to maintain the pressure differentials necessary to prevent backflow of contamination to occupied spaces of the building. An exhaust system also provides a vent for relief of pressure and hot air and a means for removing radioactive and potentially radioactive smoke before the air is released to the atmosphere. In these cases, the effect of the fire on the air cleaning system and its components becomes an important consideration. In many cases the final filters and fan, or a redundant set of filters and fan, must be operable during and following an emergency. If the building is zoned to control airflow from areas of less hazard to areas of greater hazard, pressure differentials between zones must be preserved to prevent pressurization of the contained space in which the fire occurs and to prevent backflow of contamination. Even when the ventilating system can be shut down in the event of a fire, protection of the final filters is important to provide for cleanup of the contaminated air in the building after the fire has been extinguished.

Five hazards to the final air cleaning unit which arise from fire situations are (1) heat and hot air that can (a) damage filters, (b) ignite dust accumulated in ducts or filters, and (c) distort metal parts to the point that filters are bypassed or fans and dampers are made inoperable; (2) sparks and burning trash that can ignite dust and melt holes in the filter media; (3) smoke that can plug demisters, prefilters, and HEPA filters to the point that system airflow is seriously reduced and/or the filters are ruptured due to the increased resistance; (4) overpressure due to air expansion which, when coupled with smoke plugging, can lead to rupture of the filters; and (5) droplets of spray from sprinklers or particles of other types of fire extinguishing agents, which can perforate filter medium, plug filters, or lead to reduction of their structural properties.

The first line of defense against duct and filter fires is the development and enforcement of safe operating practices in the contained and operating spaces served by those ducts and filters. This means eliminating one or more of the basic fire elements—fuel, ignition source, or oxygen. It includes control over the kinds and quantities of combustible liquids and gases in contained spaces; control of hot plates, burners, furnaces, and other sources of heat or flame; and sometimes, for totally contained spaces such as glove boxes or hot cells, inerting of the box or cell environment with nitrogen, argon, CO_2, or other gas. Safe operating practices also include (1) the development and rehearsal of preplanned fire- and damage-control procedures in the contained and occupied spaces of the building and (2) means for rapidly detecting and suppressing a fire. To date there has been no case of loss of containment due to fire in any ERDA facility equipped with a properly designed sprinkler system.[27]

Conventional fire protection practices, such as the provision of fire dampers in ducts where they pass through a fire wall or floor, are sometimes ignored or discounted in the design of nuclear ventilation and air cleaning systems on the basis that they are not needed. Such established fire protection practices should not be omitted without careful consideration of the consequences. In most cases, customary fire protective design practices should be followed in the design of air-conditioning and ventilation facilities for "cold" (Zone IV) regions of the building.

2.5.3 Power and Equipment Outage

The design for emergency must plan for the probable occurrence of power and equipment (particularly fan) failures. Such failures, if not properly planned for, can result in a contamination hazard to the public or operating personnel, particularly in buildings with zone ventilation where airflow must be maintained to preserve pressure gradients between zones and to prevent backflow of contaminated air to occupied spaces. Possible emergency measures include redundant fans, redundant fan motors (perhaps served from independent power sources), and alternate power supplies (e.g., steam turbine or emergency diesel-electric generator). Where continuous airflow must be maintained, facilities for rapid automatic switching to an alternate fan, power supply, or emergency source, or to a standby air cleaning unit, are essential. However, if brief interruptions of flow can be tolerated, manual switching may be permissible at less expense. In any event, visible and audible alarms should be provided, both locally and at a central control station, to signal the operator when a malfunction has occurred. In addition, indicator lights to show the operational status of fans and controls in the system should be provided in the central control room.

2.5.4 Air Cleaning System Layout Considerations

The layout and location of air cleaning facilities can have a direct bearing on the system's capability of effecting control under upset conditions and of limiting the adverse consequences of such an upset.

Compartmentation and Segmentation. A higher degree of control is required in the event of a fire, explosion, equipment outage, or other system upset if the air cleaning system is segmented or if the individual air cleaning units are compartmented. Segmentation permits isolation of a damaged unit and minimizes the chance that the entire system will become inoperable at the same time. Series compartmentation (see Fig. 2.10) is employed in some potentially high-risk applications to permit further isolation of the less critical air-pretreatment facilities (demisters, prefilters) from the more critical final HEPA filters and adsorbers. Series parallel arrangement of a central exhaust filter system that handles high-specific-activity alpha-emitting materials is shown in Fig. 2.12. In the event of fire or equipment damage in any one housing of this system, in the prefilters, or in the HEPA filters, the housing can be isolated and the remainder of the system kept in service. Also, any one of the housings can be isolated for testing or filter change (under normal operating conditions) without interruption of work being conducted in the building. NRC Regulatory Guide 1.52 recommends that the installed capacity of any one air cleaning unit be no greater than 30,000 cfm to permit more effective control in the event of an emergency and to permit more reliable surveillance testing of the HEPA filter and adsorber stages of the unit.[18]

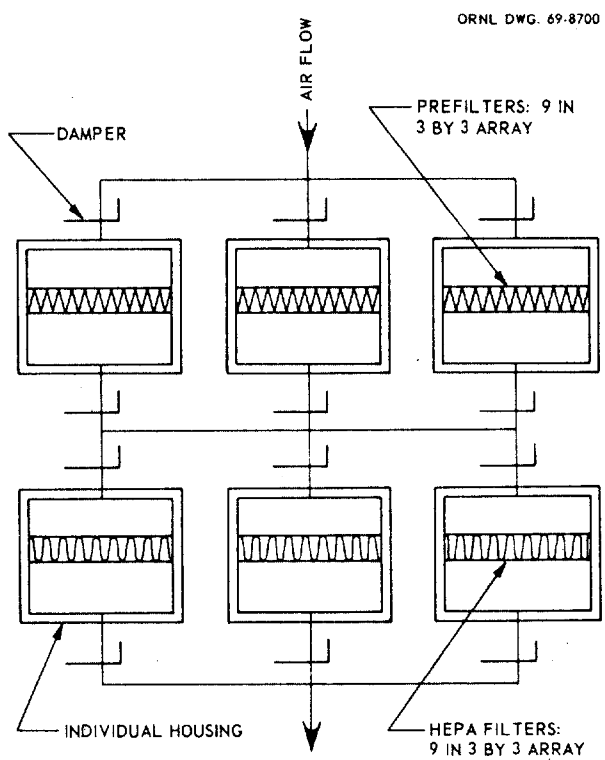


Fig. 2.12. Series-parallel arrangement of central exhaust filter system of a high-hazard radiochemical laboratory. Note dampers that permit isolation of any housing without stopping exhaust airflow.

Redundancy. Redundant air cleaning facilities are often required in potentially high-risk operations, such as reactors and radiochemical plants, to ensure continuous ventilation in the event of failure of an on-line air cleaning unit. In the case of reactor post-accident cleanup systems, redundant air cleaning units are required even though the system is normally in a standby condition. Figure 2.13 shows the segmented, redundant, normal off-gas and building-exhaust air cleaning systems of an experimental water-cooled reactor with vented containment. Of the two units of each system which are normally on-line, one is capable of meeting exhaust requirements when the building supply fans are shut down in the event of an emergency. High-quality isolation dampers are essential in redundant systems not only to protect the off-line units when not in service but to prevent bypassing of the air cleaning system through a damaged off-line air cleaning unit.

Location of Air Cleaning Facilities. The location of filters, fans, and other air cleaning components can play a major part in minimizing component damage and spread of contamination in the event of a fire, system upset, or other emergency. A common but undesirable practice has been to install such items in random locations in attics or unused building spaces. Figure 2.14 illustrates a type of filter installation in which a wood-cased filter was simply clamped between two flanged duct transitions in an open attic

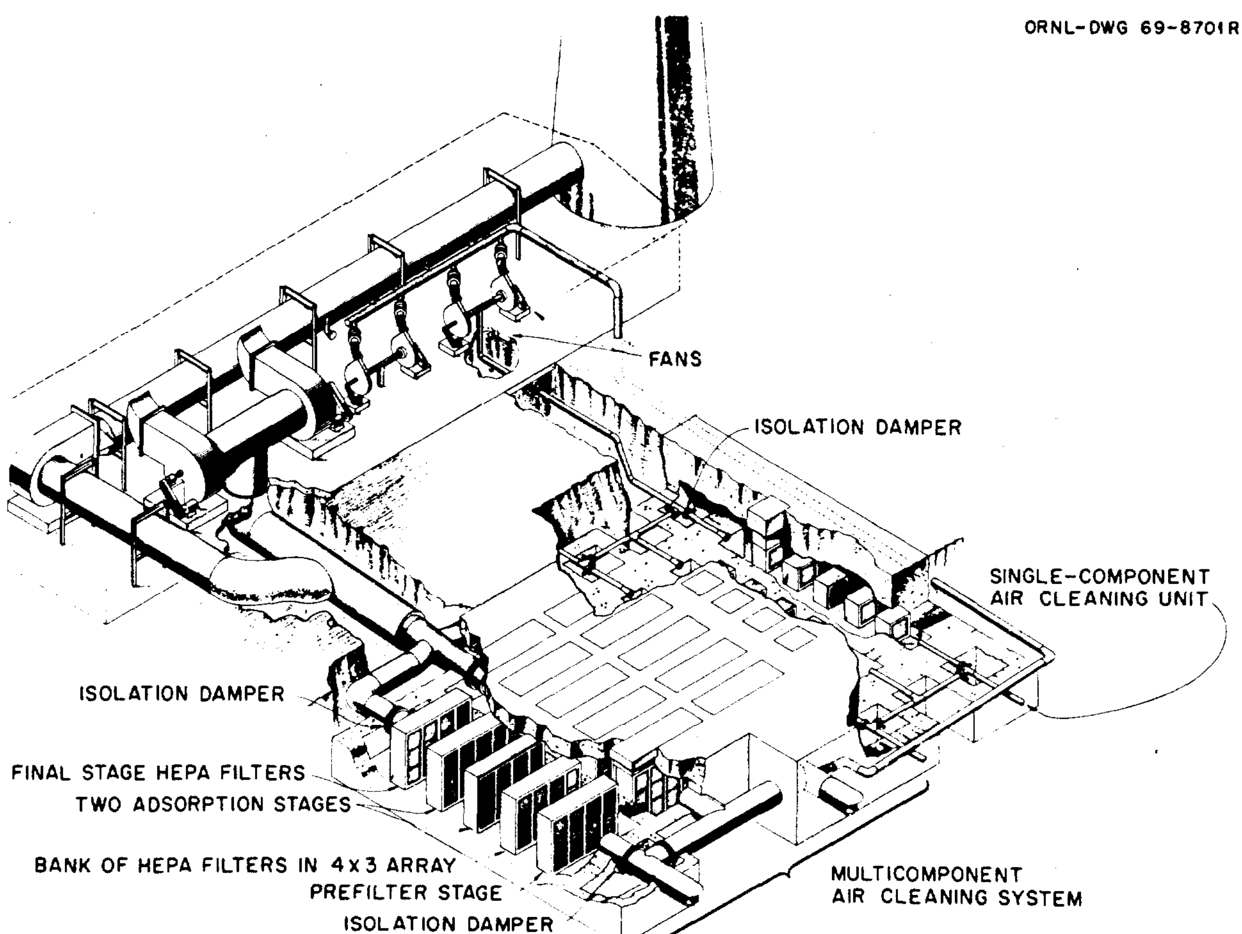


Fig. 2.13. Air cleaning facilities of an experimental reactor, illustrating application of the suggested nomenclature for nuclear air cleaning systems. Two parallel air cleaning systems are shown, one a multicomponent installation, the other a single-component installation. The components of the multicomponent system are installed in banks arranged in a 4 by 3 array; the system has an installed capacity of 36,000 cfm, with 12,000 cfm installed capacity in each of the three air cleaning units. In each of the systems, two units are capable of meeting normal system airflow needs, and one is capable of meeting airflow requirements under upset conditions; all units can be isolated by means of the isolation dampers. The systems are segmented, redundant, isolable, and branched.

space. There is no floor or catwalk adjacent to the filter, with the danger that service personnel risk falling through the ceiling to the room below, and access is limited by the adjacent hangers and ducts. Furthermore, because the location is in an open attic space, dropping a used filter during a filter change, or breach of the wood filter case in the event of a fire, would result in the spread of contamination throughout the entire attic, which would be difficult, if not impossible, to clean up. In-duct installations of this type, in which the wood filter case is part of the pressure boundary, do not conform with NFPA 90A.[28,29]

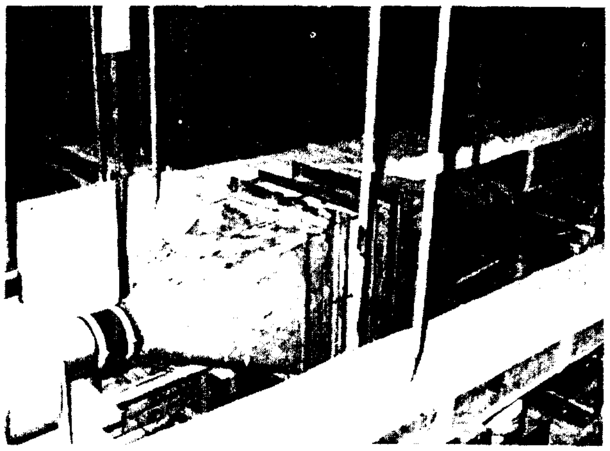


Fig. 2.14. An illustration of poor filter installation practice. Note unprotected wood-cased filter simply clamped between two transitions; difficult access for service; location in open attic; lack of floor or catwalk.

Figure 2.15 illustrates another example of poor filter installation and location. The location of the light troffer indicates that the air cleaning unit (which is provided for control room ventilation in a nuclear reactor) is located about 20 ft off the floor, and access is seriously impeded by hangers, cable trays, piping, and other equipment. This unit is a wood-cased chemical, biological, radiological (CBR) filter which, like the filter installation shown in Fig. 2.14, does not comply with NFPA 90A. Again, this unit is located in an open and normally occupied building space where a serious spread of contamination could result if the filter were dropped during service or breached in an accident or fire. Furthermore, fire external to the filter could also breach the filter case and permit contamination to spread from the room to other portions of the building. Figure 2.10 illustrates better practice by showing an air cleaning facility installed in a large room that can be isolated as a

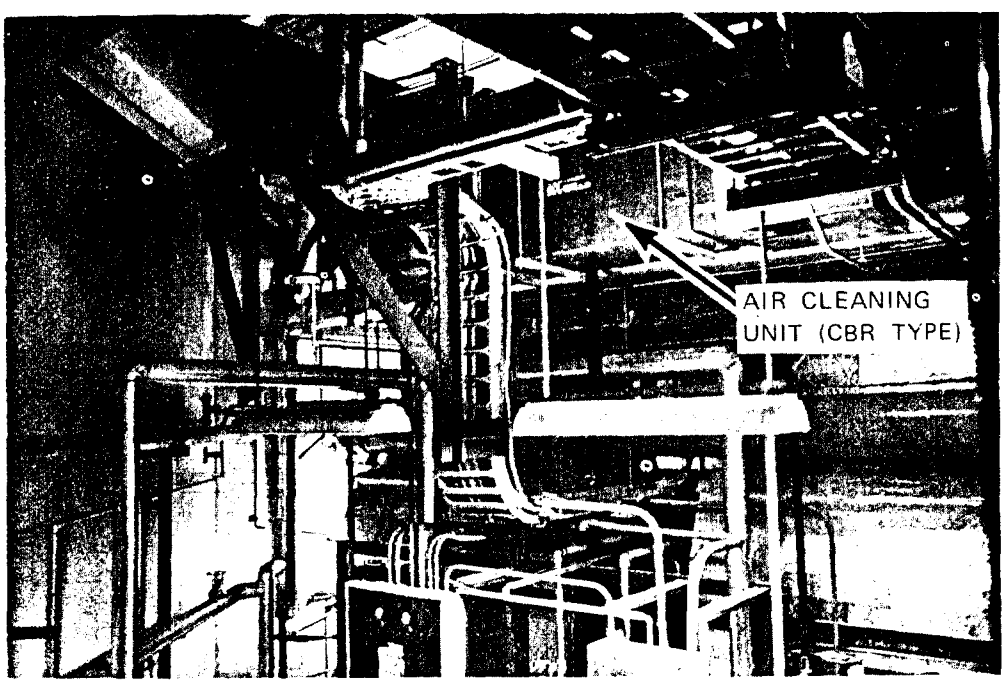


Fig. 2.15 An illustration of poor filter installation practice. Arrow points to wood-cased CBR filter. Light troffer indicates that height above floor is about 20 ft, requiring that ladders be brought in to gain access to the unit. Note cable tray, hangers, piping, and other obstructions.

radiation zone in the event of an emergency or spill without risking contamination of adjacent facilities.

Another common practice has been to install ducts and filter housings on the roof of a building which are accessible only over the roof. In the event a used filter is dropped during maintenance, there is a potential for contamination spread not only to a surface (the roof), which would be difficult to decontaminate, but to the atmosphere as well. For all systems, but especially for potentially high-hazard systems, it is recommended that all air cleaning components, including ductwork, be located inside a building space to provide a secondary containment against breach of the pressure boundary. Preferably, such building spaces should be heated to minimize condensation in the ducts during the winter months, and they should be easily accessible for inspection and service. Housings should be located in rooms that can be isolated during service or an emergency and that have walls and floors that can be easily decontaminated in the event of a spill. As a minimum precaution, the general area surrounding the housing should be one that can be cordoned off as a contamination zone. Off-the-shelf bag-out housings of the type shown in Fig. 2.16 are being used increasingly for single-filter installations. Although the bag-in bag-out provisions of these housings offer a measure of protection against spills during service operations, the plastic bags employed can be easily torn by the sharp corners of steel-cased filter elements and adsorber cells. It is recommended, therefore, that these caissons be installed in isolable rooms or controlled building spaces, at least in those cases where intermediate to high-level radioactive material is, or could be, present in the duct. Additional information on caissons and bag-in bag-out filter installations is given in Chap. 6.

2.6 MULTISTAGE FILTRATION

Although a single stage of HEPA filters is sufficient to meet most decontamination requirements, two, three, or even more stages may be required to meet the stringent requirements of facilities in which plutonium and other transuranic materials are handled. Multistage HEPA filtration is also employed to increase system reliability through series redundancy.

2.6.1 Series Redundancy

Installations such as the ERDA national laboratories and production facilities which have lived with radiation on a day-to-day basis for many years have found it necessary to employ series

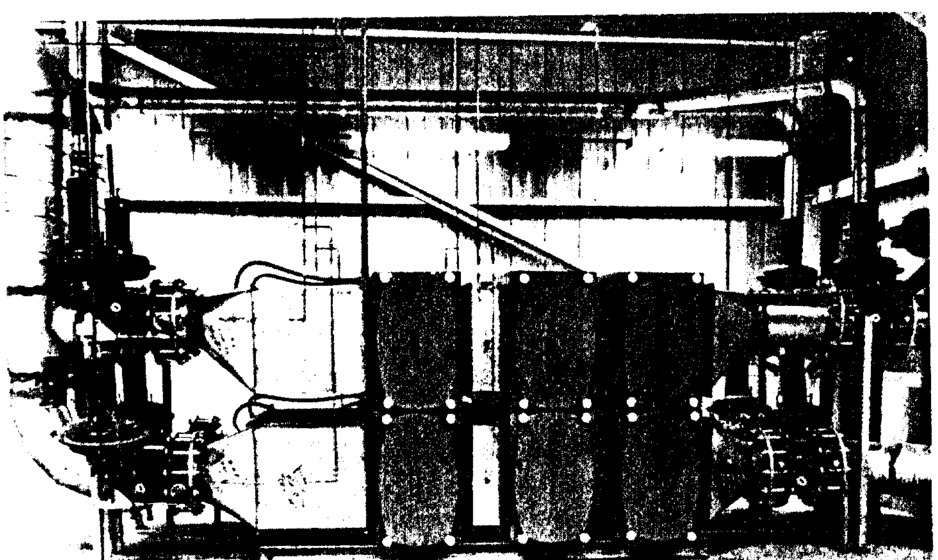


Fig. 2.16. Exhaust air cleaning system of radiopharmaceutical company. System is 1000-cfm capacity with isolable redundant branch. Each branch contains one HEPA filter and two type I (pleated bed) adsorber cells in series. Filters and adsorber cells are installed in bag-out housings. Courtesy MSA Research Corp.

redundancy of HEPA filters in exhaust and air cleanup facilities for Zone I, and often Zone II, containments. The purpose is to increase the reliability of the system by providing backup filters in the event of damage, deterioration, or failure of the first-stage filters. As noted in Sect. 2.2.1 (item 2 under air handling systems), each stage of filters must be individually testable if credit for redundancy is to be claimed. That is, if the stages are not individually testable, the combination of two or more stages must be considered as only a single stage from the standpoint of reliability. On the other hand, each untestable stage contributes to the overall filtration efficiency of the combination, although not to an extent equivalent to the nominal stage efficiency of 99.97%(DF = 3333); a maximum efficiency of 99.8% (DF = 500) has been allowed in the past for untestable second- and third-stage filters, with full credit for the first stage.[30]

Redundant stages should be well spaced, the first often being a duct-entrance filter in a room, glove box, or hot cell, and the second being the final filters of a central exhaust system. In some systems, as for example the ESF air cleaning units of nuclear power plants (shown in Figs. 2.10, 2.13, and elsewhere in this handbook), the series-redundant filter banks are installed within the same housing. In any event, redundant stages should be spaced sufficiently far apart to allow for effective in-place testing and inspection of both faces of the filters; they should not be installed back-to-back to one another or to other components of the system such as prefilters or adsorber cells (see Figs. 4.23 and 9.2).

2.6.2 Increased Decontamination Factor (DF)

The particle sizes of plutonium and plutonia aerosols generated in chemical operations employed in nuclear fuel fabrication and reprocessing fall within the range of the size of maximum penetration (SMP) for HEPA filters, 0.07 to 0.3 μm light-scattering mean diameter (LMD); although 0.3 μm LMD is considered the SMP for dust and other unit-density particles, the SMP for high-density particles, such as plutonium, is substantially higher; the aerodynamic mean diameter of plutonium particles formed by condensation is thought to lie between 0.4 and 0.7 μm.[30] A HEPA filter, by definition,[31] has a minimum filtration efficiency of 99.97% (DF = 3333) for 0.3-μm particles (although most of the HEPA filters currently being validated by the ERDA Quality Assurance Stations exhibit DFs on the order of 10^4). Current NRC Regulatory Guides recommend a total plant DF of at least 10^{11} for plutonium in gaseous effluents. Although some decontamination is effected by plant operations, the greatest portion must come from the HEPA filters, which means that two, three, or even more stages of filters may be necessary.

Theory predicts that the primary mechanisms in the arrestance of particles by a HEPA filter are diffusion and inertia; the effectiveness of these mechanisms varies with particle size, airflow velocity through the medium, and, to a lesser extent, particle density as shown in Fig. 2.17. Direct interception, or impaction, is a secondary mechanism that is independent of these parameters. As evident from Fig. 2.17, these mechanisms combine to produce a statistical average DF, not an absolute value for a given particle size. For this reason, the effect of adding stages of HEPA filters is multiplicative and does not produce a screening effect that theoretically results in an absolute minimum DF for any given particle size. (In practice, however, some screening of particles substantially larger than the SMP can be expected.) In theory, therefore, the DF of a multistage HEPA filter installation would be DF_f^n, where DF_f is the definition DF of the HEPA filter (3333) and n is the number of stages. Recent work by Ettinger et al.[32] at the Los Alamos Scientific Laboratory suggests that this theory is essentially true; DFs of 10^4 for stages one and two and of somewhat less than 5×10^3 for the third stage of a three-stage system, with an average DF of 5×10^3 for each of the three stages, were determined.[30] These results were obtained in a small-scale test system (about 25 cfm) in which conditions were idealized by eliminating gasket leakage and employing filter units that exhibited a test efficiency (according to ERDA Quality Assurance Station testing) of greater than 99.99%.

Earlier less definitive tests and experience had indicated substantially lower values of DF in the second and third stages, and conservatism suggests that values lower than those obtained in the Los Alamos tests should be used in practice. Conservatism also suggests that a value no higher than DF_f (3333) be used for the first stage and probably somewhat less to allow for filter degradation under service conditions. Although DF improves with dust loading of the filter, aging and exposure to moisture and corrodents may decrease the ability of the filter to maintain the higher DF under system upset conditions. For purposes of estimating the capability of a

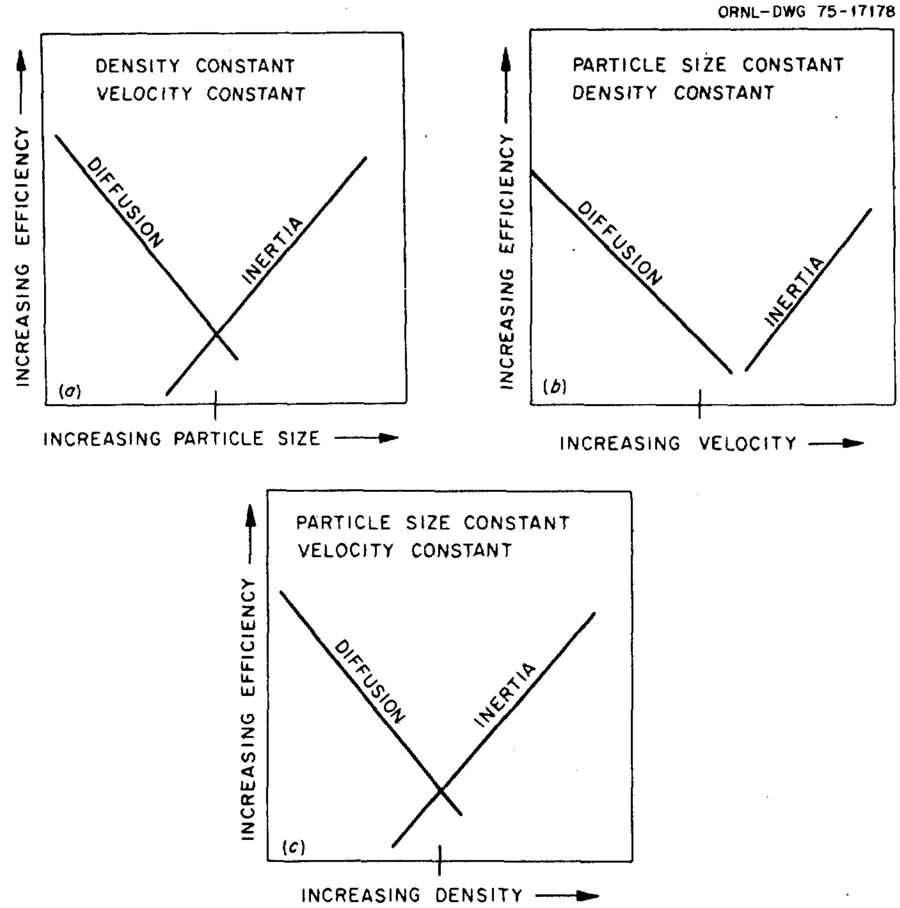


Fig. 2.17. **General effect of principal mechanisms that affect the arresting efficiency of the HEPA filter.** (*a*) Effectiveness of diffusion mechanism decreases with increasing particle size; effectiveness of inertial mechanism increases, at a given velocity. (*b*) Effectiveness of diffusion decreases with increasing velocity; effectiveness of inertial effects increase, for a given particle size. (*c*) For a given particle size and velocity, increased density decreases effectiveness of diffusion and increases effectiveness of inertial effect.

multistage HEPA filter installation under normal operating conditions, a DF of $(3 \times 10^3)^n$ can be safely used with systems that adhere to the design, construction, testability, and maintainability principles of this handbook or of ANSI N509.[33]

For purposes of assigning safety credit in facility safety analysis reports, however, consideration must be given to possible degradation of the filters under upset conditions. This requires that substantially more conservative DFs be used, particularly for the first-stage HEPA filters that would probably receive the brunt of any adverse effects due to a system upset. The concensus of a meeting held in the Albuquerque AEC Operations Office in 1971 to review filtration requirements for plants in which plutonium is handled[34] was that a safety credit of 2×10^3 should be allowed for each stage of a system in which each stage is individually testable for the normal operating situation. It was recommended that lower values (not stipulated) be used for the accident condition and for the system in which stages were not individually testable. The value of 2×10^3 is considered low for normal operation in view of the Los Alamos work and the quality of filters now being received at the ERDA Quality Assurance Stations (most exhibit a penetration $<0.01\%$ or an efficiency $>99.99\%$). In view of the fact that no thorough hazard analysis exists to predict what might happen in an accident, a lower DF of 5×10^2 for the first stage and $(1 \text{ to } 2 \times 10^3)$ for each of the remaining stages appears defensible for the accident condition,[28] assuming that each stage is individually testable. If stages are not individually testable, the recommendations of Sect. 2.6.1 apply; that is, the additional stages should also be given a safety credit of no more than 5×10^2.

2.7 AIR SAMPLING

Air samples are often taken from the stack or other locations downstream of the filters to monitor the amount of radioactive material being released to the atmosphere. If the sampling system is not properly designed, underestimation of released radioactive material may result. The element often at fault is the sampling line itself. If the sampling line is too long or too small in diameter (relative to flow velocity in the line), it may act as a diffusion tube to remove small particles or as an inertial separator to capture large particles before they can reach the counting and recording requipment. Sharp-angle bends, valves, and other flow restrictions must be minimized to avoid losses due to inertia, impaction, and impingement. Horizontal runs must be minimized to avoid gravitational settling. Conduit diameter must be large enough and consistent with flow velocity to minimize diffusion losses and turbulence that can cause migration of particles to the conduit walls, where they may be captured (turbulence in sampling lines can take place at a Reynolds number of 1200 or lower).[35] The optimum sampling line diameter, considering both line losses and practical limitations on line size, can be found from the equation [36]

$$d=\frac{Q}{150}\,, \tag{2.4}$$

where

d = diameter of sampling conduit, cm
Q = sampling rate, cm^3/sec.

Sampling nozzles should be sized for isokinetic inlet velocity. Sampling lines should be vertical, insofar as practicable, and should be as short as possible between collector nozzle and counting instruments (some stack sampling instruments are located on the stack at the same level as the sampling point). Sample lines should be stainless steel or copper; they must be clean and smooth on the inside and should be detachable to permit occasional field cleaning. Oil and moisture on the inner surfaces of the sample lines will trap particles and give false readings. Cleaning by procedures that meet the requirements of ASTM A380[37] is recommended.

REFERENCES FOR CHAP. 2

1. "Standards for Protection Against Radiation," *Code of Federal Regulations*, Title 10, Part 20 (10 CFR 20).

2. "Reactor Site Criteria," *Code of Federal Regulations*, Title 10, Part 100 (10 CFR 100).

3. "Licensing of Production and Utilization Facilities," *Code of Federal Regulations*, Title 10, Part 50 (10 CFR 50).

4. "Design Criteria for Radiochemical Plants and Laboratories," *Procedures and Practices for Radiation Protection-Health Physics Manual*, Oak Ridge National Laboratory, Appendix A-11, Jan. 8, 1974.

5. Numerical values can be relaxed or increased, depending on the requirements for the operating conditions and the DBA for that facility.

6. *TLVs—Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment*, American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio (issued annually).

7. "Report of International Atomic Energy Agency (IAEA) Symposium on Airborne Radioactivity," *Nucleonics Week*, 8(9), 7 (July 20, 1966).

8. R. E. Harrington, "Fine Particulates—The Misunderstood Air Pollutant," *J. Air Pollut. Control Assoc.* 24(10), 927–29 (October 1974).

9. K. T. Whitby et al., "The ASHAE Air-Borne Dust Survey," *Heat. Piping Air Cond.* 185–192 (November 1957).

10. P. R. Austin, "Personnel Emissions in Laminar-Flow Clean Rooms," *Contam. Control*, 5(7), 29 (July 1966).

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